Chapter 20

Bio and Nanosensors: Theory and Applications in Agriculture

V. Ramamoorthi[1]*, S. Srivignesh[2], S. Marimuthu[1] and K.S. Subramanian[3]

[1]Department of Nano Science and Technology, Tamil Nadu Agricultural University, Coimbatore – 641 003, Tamil Nadu
[2]Department of Horticulture and Floriculture, School of Life Sciences Central University of Tamil Nadu, Thiruvarur – 610 005, Tamil Nadu
[3]Director of Research, Tamil Nadu Agricultural University, Coimbatore – 641 003, Tamil Nadu
**e-mail: vasudevanramamoorthi@gmail.com*

Biosensors are a special type of bioelectronics devices that are suitable for detection and quantifying the wide range of chemical and biological parameters present in various practical application (biosecurity, environmental, agricultural, pharmaceuticals and food and animal industries). The term biosensor was first introduced by Clark and Lyons in the year 1962 after the invention of enzyme based electrode system. Biosensors can be defined as a compact and highly specific analytical device that transforms biological signals into electrical outputs, when an analyte and bio-recognizing material combines with the presence of signaling transducers (Nigam and Shukla, 2015). The electrical outputs recorded from the biomolecular interactions were amplified, processed and displayed through the support of computer-aided readouts; in that way, the users can understand the association that occurred between ligand and targeted material (Figure 20.1). However, this strength of an electrical current produced from the interaction was directly proportional to the concentration of targeted analyte, which are capable to afford semi-quantitative and quantitative analytical information (Wang *et al.*, 2014). According to IUPAC recommendations "a biosensor is an independently integrated receptor transducer device, which is capable of providing selective

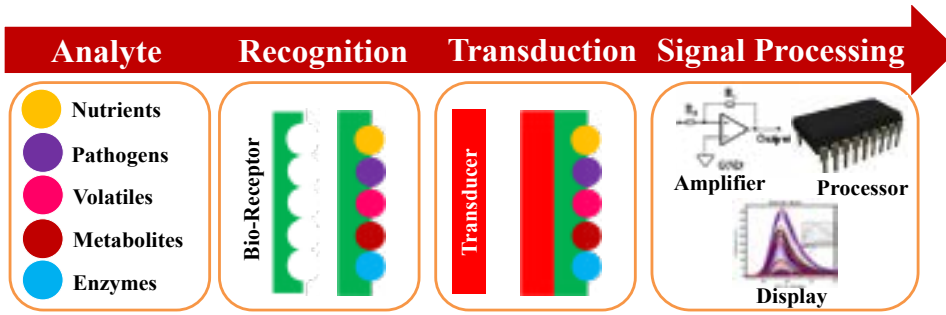

Figure 20.1. Schematic Workflow and Components of Typical Biosensor.

quantitative or semi quantitative analytical information using biological recognition element (Thevenot *et al.*, 1999)". The fundamental working principles involved in the biosensors are "bio-recognition" (biological component) and "bio-sensing" (electronic component) (Karunakaran *et al.*, 2015). The main objectives of the biosensor are to provide accurate, reliable, and quick information about the concerned analyte in real time. In this chapter, the current status of different biosensors and their mechanisms involved in the detection of various analyte with respect to agricultural applications are detailed.

Basic Principles of Biosensor

Biosensor works on the basic principle of signal transduction. This is an electronic device that composed of transducer and biorecognizing elements that may be a protein, antigen or a nucleic acid (Neethirajan *et al.*, 2005). The physico-chemical (pH, temperature, mass change, *etc.*,) changes produced during the binding of analyte to the biological material forms a bound analyte, which in turn produces biological signals that can be converted and amplified with the help of signal transducers (Grieshaber *et al.*, 2008).

Components of Biosensor

A biosensor consists of four main components: (a) analyte (b) receptor-biological recognizing system, (c) physico or chemical transducer – convert biological signals into electrical signals, and (d) microelectronics – amplifier, processor and display (David *et al.*, 2008). The basic components involved in the construction of typical biosensor are represented in Figure 20.1.

Analyte

A substance of interest that is exposed for measurement (or) analysis. For example, cadmium is an "analyte" for biosensor designed to measure environmental quality.

Bioreceptor

A biological molecular species that utilizes biochemical mechanism for specific interaction. Antibody/antigen, nucleic acid, DNA/RNA, enzyme and cell

organelles are some of the commonly used form of bioreceptors. It is a significant and distinguishing feature of biosensor that comprises biorecognition system of sensor towards the target analyte.

Transducer

Transducer is an electronic circuit that converts one form of energy (biological signals) into another form (electrical signals). This practice of energy exchange is popularly called as signalization.

Electronic Systems

The electronic system consists of complex electronic circuits that perform signal amplification, processing and displaying of transduced signals from analogue into digital form. The indications on the display might be graphic, tabular, numeric or an image depending on the requirements.

Classification of Biosensor

The biosensors can be classified on the basis of biological sensing element (enzyme, microbe, proteins, antibodies *etc.*,), bio sensing method (affinity, metabolic or catalytic) and type of transducer (electrochemical, optical or mass based) engaged in the detection procedure. The various classifications of biosensors are depicted in Figure 20.2.

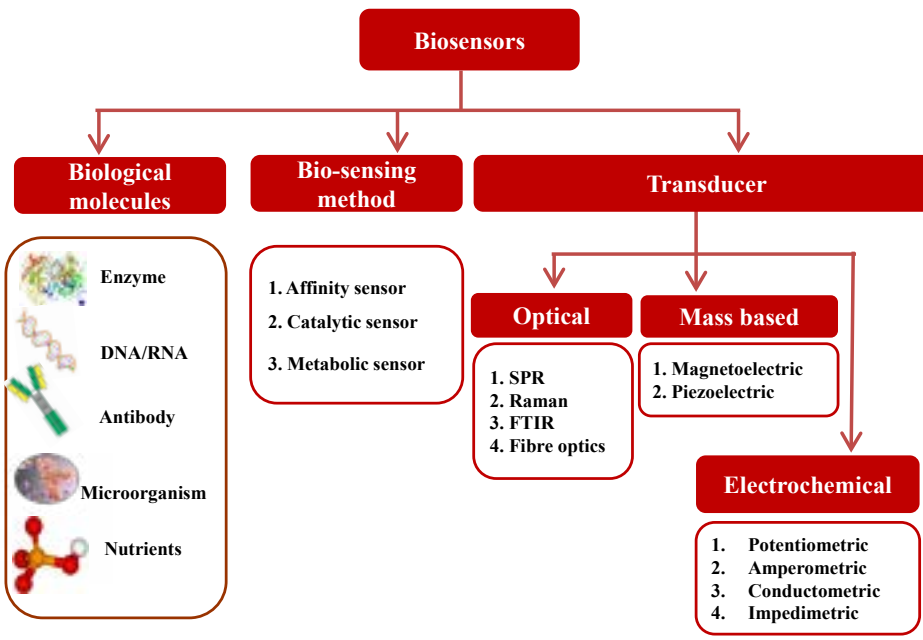

Figure 20.2. Classification of Biosensors Based on Biological Molecule, Biosensing Method and Type of Transducer.

Classification of Biosensors Based on Bioreceptor

A bioreceptor is molecular species that utilize a biochemical mechanism for specific recognition and responsible for the binding of targeted analyte to the surface of signal transducer. Bioreceptors are generally divided into five major classes: antibody/antigen, enzyme, cellular structure/cell, nucleic acid/DNA and biomimetic or synthetic (Salgado *et al.,* 2011). The most common forms of bioreceptors used in biosensing are: a. enzymatic interactions; b. antibody-antigen interactions; c. nucleic acid interactions; d. microbial or cellular interactions; e. interactions using synthetic materials. The antibodies and enzymes are the leading groups of biological molecule/bioreceptor that are widely used in biosensor applications (Monosik *et al.,* 2012).

Enzyme Bioreceptor: Biosensor

Enzyme is a widely used protein molecule that catalyzing a particular substrate into a product without being consumed in (Figure 20.3). The bioreceptor are mounted on the transducer surface through covalent attachment, adsorption, gel entrapment or an electrochemically engendered polymer. Compared with chemical reactions, enzymes are fairly fast and highly selective and they can be used in combination with different transduction mechanisms. The mechanisms of these bioreceptors can comprise: (a) transformation of the bound analyte into a sensor measurable product (b) detection of enzyme activated or inhibited analyte and (3) evaluation of modified enzyme properties acted upon interaction.

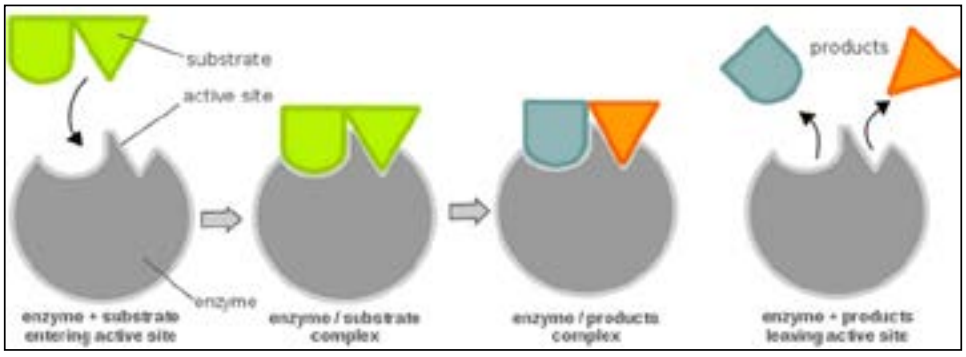

Figure 20.3. Catalytic Mechanism of Enzyme Bioreceptor and Targeted Substrate. *Courtesy*: Shivangi Soni, 2016.

Antibody Bioreceptor: Immunosensor

Antibody bioreceptors works on the principle of antigen-antibody interactions that can be transduced directly into a quantifiable electrical signal. Antibodies (immunoglobulin/glycoproteins) are heavy globular plasma proteins (50 kDa) that are composed of two light chains and two heavy chains forming the well-known Y shaped structure. Schematic demonstration of Y-shaped structure of an antibody is shown in Figure 20.4. These antibodies secreted in the animal cells by immunological responses to the foreign (antigen) agent (Sharma *et al.,* 2016).

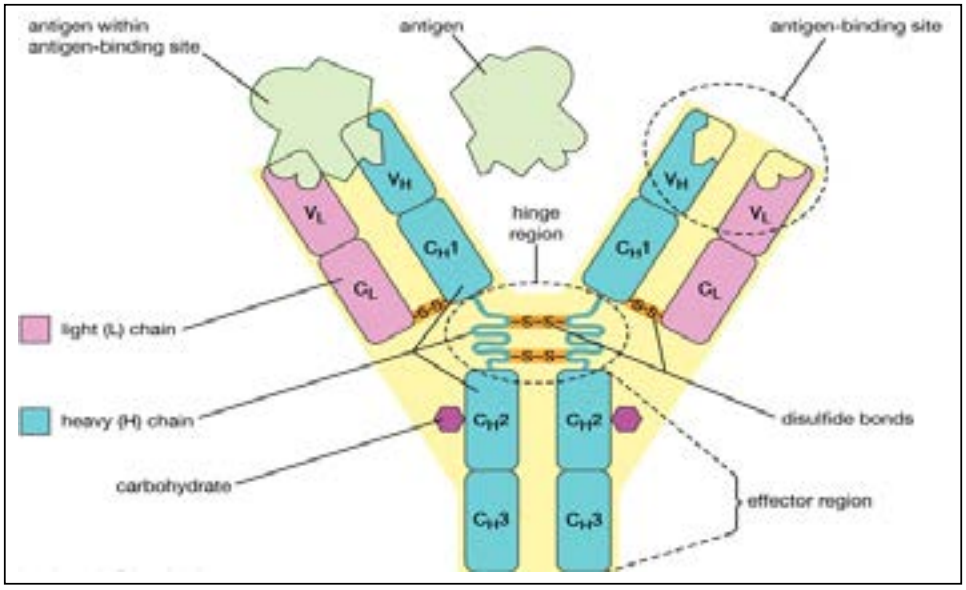

Figure 20.4. Schematic Demonstration of Y-shaped Structure of an Antibody
Courtesy: https://www.britannica.com/science/antibody.

Antibodies are sensitive to changes in ionic strength, pH, temperature and chemical inhibitors. Monoclonal (highly specific but identical) and polyclonal (highly sensitive but less specific) antibodies are commonly employed in the construction of Immunosensors. Monoclonal antibodies produce significantly less background staining than polyclonal antibodies, because of their specificity towards specific antigens in the presence of interfering molecules (Karunakaran *et al.,* 2015).

Nucleic Acid/DNA Bioreceptor: Genosensor

Nucleic acids biosensors are used to detect the individual nucleotides based on nucleic acid sequencing processes and that are being developed for rapid and inexpensive testing of genetic and pathogenic diseases. DNA is highly suitable nucleic acid for biosensing applications due to the nature of base-pairing interactions among complementary sequences. DNA biosensor is a device that can combine with specific DNA probe and signal transducer through hybridization techniques then the target DNA is captured on the recognition layer, and the resulting hybridization signal is transduced into a usable electronic signal for display and analysis (Liu *et al.,* 2012). This recognition mechanism depends on the method of signal transduction (electrochemical, mechanical or optical). DNA techniques like recombination, hybridization and amplification are all based on the structure of double helix DNA. The general structure of DNA and DNA hybridization is displayed in Figure 20.5.

Microbial Bioreceptor: Microbial Biosensor

The enzymes or proteins present in the living organisms can act as a bioelement to detect specific molecule or state surrounding environment based

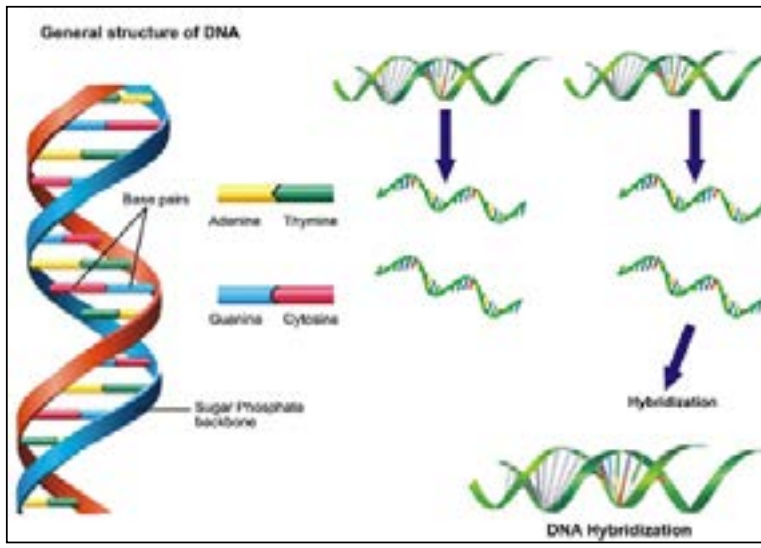

Figure 20.5. General Structure of DNA and DNA Hybridization.

on the measurement of their mechanism, in many cases accompanied by the consumption of O_2 or CO_2. Microbial biosensor is an analytical device that immobilizes microorganisms (bacterial, fungi or virus) onto a transducer surface to generate electrical signals proportionate to the concentration of specific substrate. The immobilization process determines the quality of the signal transferred from microorganisms to the transducer. Microorganisms have been integrated with a variety of transducers such as conductometric, potentiometric, amperometric, colorimetric, voltammetry, fluorimetric and luminometric to fabricate biosensor devices (Su *et al.*, 2011; Thouand, 2018).

Classification of Biosensors Based on Biosensing Method

Biosensors are broadly classified into three different types based on its biorecognition mechanism. **Affinity sensors** relay on the mechanism of reversible binding of the analyte to a specific receptor (Beyer *et al.*, 2014); M**etabolic sensors** measures the cell signals or concentration of a substrate during the interaction of analyte and biomolecule through the incorporation of metabolic signals into the signaling networks (Krejci, 2012); **Catalytic biosensors** works on the nature of secondary substrates produced during the interaction of analyte and biological elements (Li and Lu, 2000).

Classification of Biosensors Based on Transducers

A transducer is the device that converts biological signals into detectable electrical signals. The detectable electrical signals were electrochemical, calorimetric, optical magnetic or mass change in nature. The commonly accomplished biosensors based on different transduction methods are classified in one of the three main classes:

1. Optical biosensor - SPR, Raman, FTIR and Fibre optics
2. Mass based biosensor - Magnetometry and Piezometry
3. Electrochemical biosensor - Potentiometry, Conductometry, Amperometry, Impedimetry

Optical Biosensor

Optical biosensors are the most commonly used class of biosensors. The optical detection is performed by manipulating the interaction of biorecognition element with an optical field. The biorecognition procedure induces a change in the amplitude, phase, frequency or polarization of the incident light with response to the physical or chemical change (Damborsky *et al.,* 2016). The major components of optical biosensors were; light source, biological recognition element, optical transmission medium and wavelength detection system. Optical biosensors are broadly divided into methods based on the different parameter: Label free method directly measures the signals, formed during the interaction of analyte with the transducers. In contrast label based method involves the use of fluorescent tags signals to detect the target molecule (Perumal and Hashim, 2014).

Fiber optic biosensors (FOBS) are optical fiber-derived devices which use optical field to measure biological species such as proteins, cells, and RNA/DNA (Leung *et al.,* 2007). Optical sensors based on excitation of surface plasmon (electromagnetic wave), generally mentioned as Surface plasmon resonance sensors (SPR) and it was first demonstrated for biosensing in 1983 by Liedberg *et al.* (1983). SPR is a noninvasive label free method of optical biosensor used for observing real time interactions between injected analyte and immobilized biomolecule. SPR phenomenon occurs on the surface of conducting material and at the interface of two media when it was illuminated by polarized light at a specific wavelength. The reduction of reflected light intensity at a specific angle is known as resonance angle (Tang *et al.,* 2010). The principle of surface plasmon resonance (SPR) is characterized in Figure 20.6.

Mass Based Biosensor

Piezoelectric biosensors is a class of micro electromechanical systems (MEMS) highly suitable for label-free portable biosensing, which is depends on the principle of changes in oscillating crystal resonance frequency due to the interaction of analyte and bioreceptor (Pohanka, 2018). The biosensing material coated on the surface of piezoelectric material (transducer) produces electrical signal when applying mechanical stress. A crystal oscillates at a certain frequency depends on the mass of the crystal and coating. Quartz is the most commonly used single crystal which can withstand extreme thermal, mechanical and chemical stresses (Nicu *et al.,* 2005). There are two classes of piezoelectric sensors based on the type of travelling wave; Surface acoustic wave (BAW) piezoelectric sensors - propagating through the interior of the substrate; Bulk acoustic wave (SAW) piezoelectric sensors - propagating on the surface of the substrate.

Magnetoelastic biosensors are made from amorphous ferro-magentoelastic metal flim ribbons coated on a pH sensitive polymer. The magnetoelastic substance

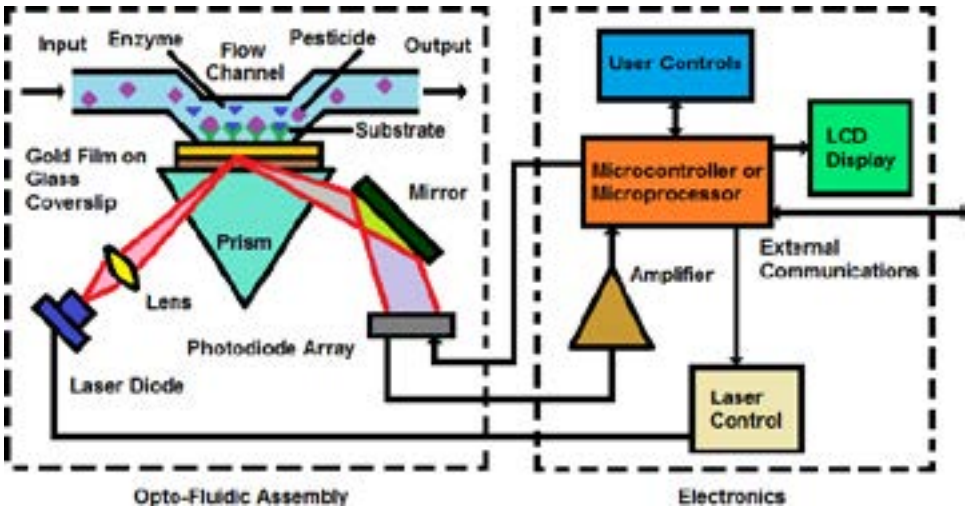

Figure 20.6. Optical Biosensor Based on Surface Plasmon Resonance (SPR).
Courtesy: Vargas-Bernal *et al.*, 2012.

changes its magnitudes (starts to oscillate emitting) when it is exposed to a magnetic field. The amplitude, frequency and damping of the oscillating magnetic field give information about the property of coated material (Zourob *et al.*, 2007). The components and schematic sketch of mass based biosensors are detailed in Figure 20.7.

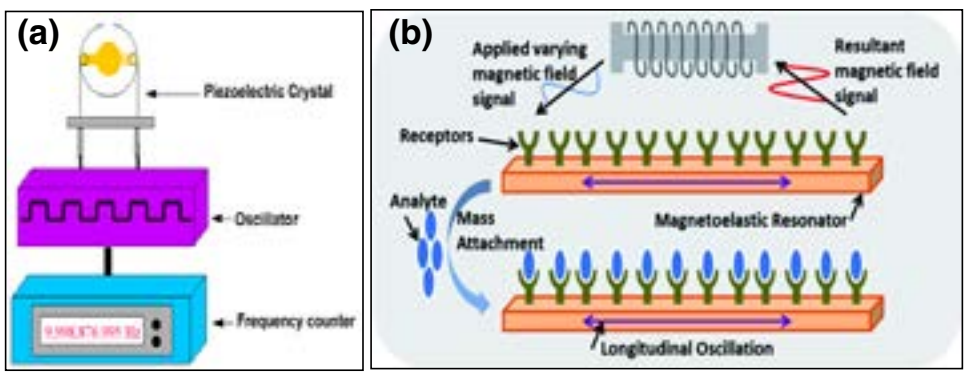

Figure 20.7. Schematic Representation of Piezoelectric (a) and Magnetoelastic Biosensors (b)
Courtesy: Shruthi *et al.*, 2014.

Calorimetric Biosensors

Calorimetric biosensors are works on the principle of calorimetric transduction that are designed to detect changes in temperature between analyte and a biorecognition element during biological or chemical reactions (Xie *et al.*, 1999). This change in temperature directly correlated to the amount of reactant or products

formed. The evolved heat change is measured using either a thermophile (ceramic semiconductor) or thermistor (MOF) and widely used for label free screening of biomolecules with more stability and sensitivity.

Electrochemical Biosensors

According to the 1999 IUPAC recommendation, "an electrochemical biosensor is a self-contained integrated device that is capable of providing specific quantitative or semi quantitative analytical information using a biological recognition element (biochemical receptor) that is retained in direct spatial contact with an electrochemical transduction element". Electrochemical transducers used to measure the current produced from oxidation and reduction reaction (Rotariu *et al.*, 2016). The electrical signal resulted by the recognition process proportional to the analyte concentration. Electrochemical biosensors can be classified into five types depending upon the nature of biorecognition event: potentiometric, voltametric, amperometric, conductometric and Impedimetric.

Electrochemical cell is a device that can generate electrical energy from chemical reactions which is comprises working electrode (WE), reference electrode (RE) and counter electrode (CE). Electrochemical analyzer is an instrument used to measure the potential or current of an analyte in an electrochemical cell. Schematics of representation of electrochemical cell and electrochemical work station are detailed in Figure 20.8.

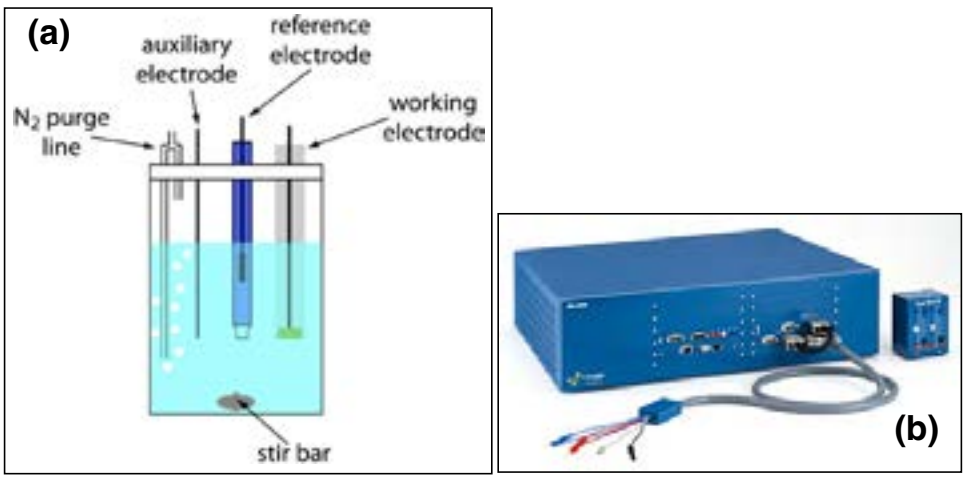

Figure 20.8. Schematic Representation of Electrochemical Cell (a) and Work Station (b).
Courtesy: mmrc.caltech.edu.

Microfluidic devices are a miniaturized version of conventional electrochemical cells that containing tunnels and chambers through which fluids are confined or flow. The behavior of microelectrode differs from conventional electrodes in that nonlinear diffusion is the predominant mode of transport. (Aryasomayajula *et al.*, 2017). In microfluidic cell three different materials were optimized as electrode:

silver-epoxy composite as pseudo-reference electrode, graphite-epoxy composite as auxiliary electrode and gold film or graphite-epoxy composite as working electrode. The performance of the microfluidic cell was categorized using cyclic voltammetry. The microfluidic electrochemical cell is represented in Figure 20.9.

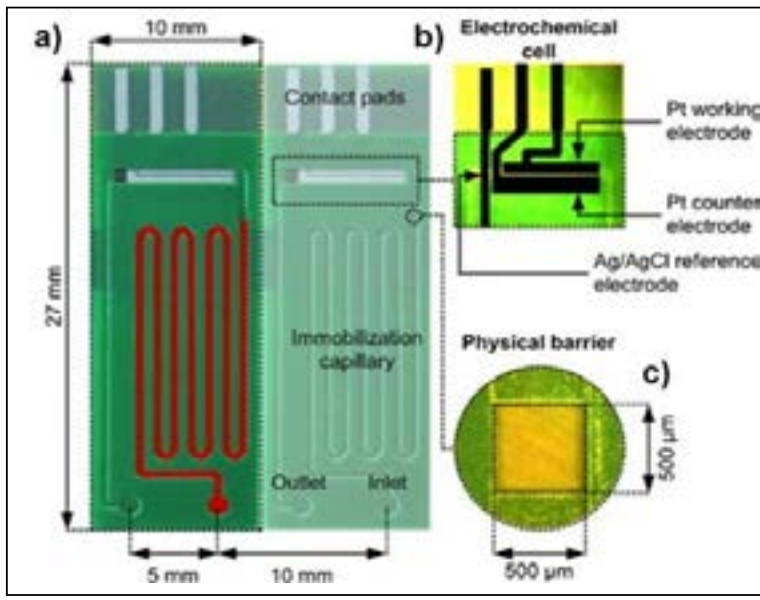

Figure 20.9. Microfluidic Electrochemical Cells.
Courtesy: Horak *et al.*, 2014.

Lab-On-Chip (LOC) or Screen Printed Electrode (SPCE) is a device that has several integrated laboratory functions on a single chip, which is normally few millimeters to several centimeters in size. The Lab-On-Chip (LOC) or Screen Printed Electrode (SPCE) device is shown on Figure 20.10.

Application of Bio and Nanosensors in Agriculture

Agriculture includes the production of crops, which have been susceptible to damage in the form of biotic and edaphic that causes severe loss in profit. Therefore, the effective way of increasing profits would be to reduce the loss of crops from natural threats (Fletcher *et al.*, 2007). Biosensors are a powerful alternative technology to conventional analytical techniques, harnessing the sensitivity and specificity of biological systems in low cost and portable devices. The need for quick and accurate sensing opens up opportunities for biosensors in many different agricultural areas -in situ analysis of nutrient and pollutants, detection and identification of pest and diseases in crops and the summary of various bio and nanosensors technologies involved in the agricultural applications are depicted in Table 20.1.

Deoxyribonucleic acid (DNA) is basic building block for all living organisms inclusive of plants providing codes for the synthesis for genes and proteins. Nanofabrication of DNA is relatively simple and complementary base pairing

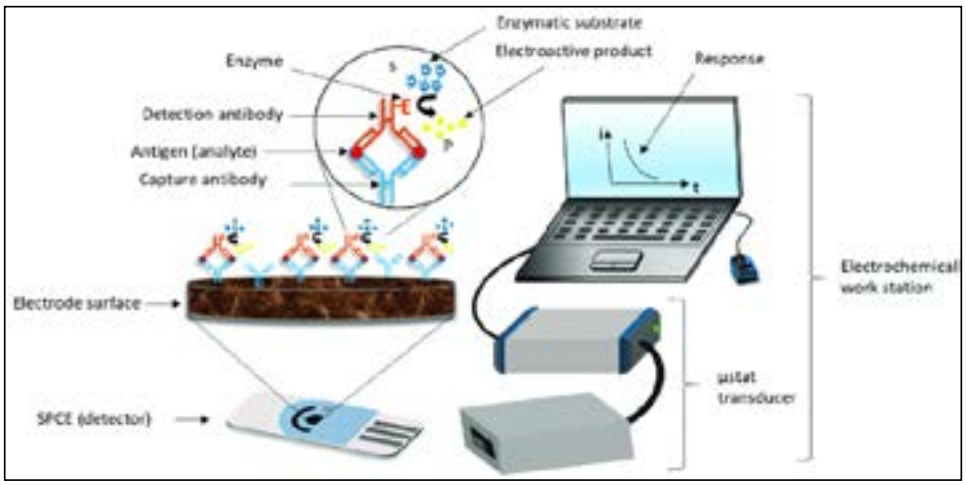

Figure 20.10. Lab-On-Chip or Screen Printed Electrode.
Courtesy: Vasilescu *et al.*, 2016.

can be effectively controlled which paved way for the DNA biosensors and DNA microarrays. DNA biosensors and DNA microarrays (DNA chips) application has successfully employed in the medical diagnostic field and potential application in agriculture is evolving fast. DNA based detections are needy in detection of forensic substances, biological contaminants and analysis gene expression patterns. The old system of DNA chip based detection systems are mainly based on binding the DNA materials to its complimentary sequence/probe which is a single stranded DNA (ssDNA) or chemically synthesized oligo nucleotides attached on the solid substrate (glass, silicon, special plastics) or in a buffer solution, allowing the target DNA to get hybridized. Generally, 10,000 to 40,000 probes are placed in each zones of 10-100 μm (Hahn *et al.*, 2005). The synthesized oligos can be directly in-situ synthesized on the surface or deposited on the chemically activated surfaces (Dufva, 2005). The Hybridized DNA is detected by means of electrochemically or by optical transduction modes which allows to study gene expression profiles of thousand genes simultaneously. Biosensor microarrays primarily used for biological detections, complete transcriptome and proteome changes of biological samples. Whereas DNA biosensors the DNA probes were directly immobilized on the transducer surface. The DNA biosensors are more robust, highly sensitive, parallel detection on multiple modes, reusable, and specifically miniature size (Lamartine, 2006). This lacks simultaneous analysis of a given phenomenon, possibility of one single application and hard to miniature these devices. DNA biosensors are capable of detecting the single base pair genetic mutations. This is highly useful in identifying the single nucleotide polymorphisms (SNP), for developing the molecular markers in plants. The genetic mutation in single gene can alter the resistance level in plants, or to identify the mutation leading to new trait (for example ovate gene in tomato). Recent technological advancements paved way to design localized surface plasmon resonance (LSPR) biosensors which have been subjected to a great scientific interest

Table 20.1. Application of Nano and Biosensors in Agriculture (Adopted from Khater *et al.*, 2017)

Target Analyte	*Sensing Strategy*	*Transduction Method*	*Nanomaterial Exploited*	*LOD*	*Reference*
Atrazine	Inhibition of tyrosinase	Amperometric	TiO_2 nanotubes	0.1 ppt	Yu *et al.*, 2010
Methyl	Inhibition of AChE	Differential pulse voltammetry	Multi-walled carbon nanotubes-chitosan nanocomposite	7.5×10^{-13}M	Dong *et al.*, 2013
Acetamiprid	aptamer	Colorimetric analysis	Gold nanoparticles	5 µM	Shi *et al.*, 2013
Glyphosate and glufosinate	Specific Double template imprinted polymers	Differential pulse anodic stripping voltammetry	Multi walled carbon nanotubes	0.35 µg mL^{-1} 0.19 µg mL^{-1}	Prasad *et al.*, 2014
Nitrate	Ion selective electrode	Potentiometric	Graphene oxide	10^{-5} M	Pan *et al.*, 2016
Nitrate	Nitrate reductase	Impedimetric	PEDOT nanofibers - Graphene oxide	0.68 mg/L	Ali *et al.*, 2017
Urea and Urease activity	Gold nanoparticles acting as a catalyst imitating horseradish peroxidase	Colorimetric pH indicator	Gold nanoparticles	5 µM 1.8 U/L	Deng *et al.*, 2016
Ganoderma boninense	DNA probe	Fluorescence resonance	Quantum dots	3.55×10^{-9}M	Bakhori *et al.*, 2013
Pantoea stewartii sbusp. *stewartii*-NCPPB 449	Immunosensor	Enzyme-linked immunosorbent assay (ELISA)	Gold nanoparticles	7.8×10^{3} cfu/mL	Zhao *et al.*, 2014
Cymbidium mosaic virus	Fibre optic particle Plasmon resonance	Immunosensor	Gold nanorods	48 pg/mL 42 pg/mL	Lin *et al.*, 2014
Trichoderma harzianum	Single stranded DNA probe	Electrochemical analysis	ZnO nanoparticles - chitosan nanocomposite	1.0×10^{-19} mol/L	Siddiquee *et al.*, 2014

in the last few years. The LSPR biosensors offer quick and multiplexing options paved way to design of lab-on-a-chip (LOC) optical biosensor platforms. Recently it was shown that the hybrid plasmonic biosensor could specially detect *Bacillus thuringiensis* Cry1Ab protein in crop samples (Ming *et al.,* 2014). For instance, Lee *et al.,* 2016 developed nanoplasmic biochip coupled with smartphone for quantitative detection of imidacloprid pesticide, similarly a LSPR based biosensor was developed to detect shinga and cholre toxins Nagatsuka *et al.,* 2013.

Masrie *et al.* (2017) developed an optical transducer; LED and photodiode based biosensor for soil nitrogen, phosphorus and potassium monitoring. Fibre optical biosensing devices have been proposed to monitor plant nutrient and water stresses (Asundi *et al.,* 2006). A low-power, low-cost dual probe heat pulse techniques (DPHP) have been proposed for monitoring real-time soil moisture status. A DPHP sensor has two probes: a temperature sensor probe and a heater probe with a power AC supply of 3.3V. To detect volumetric water content the sensor was validated with red and white clay soil samples (Jorapur *et al.,* 2015).

A graphene foam titanium nitrate nanofibers (GF–TiN NFs) based microfluidic electrochemical sensors for the detection of nitrate in agricultural soils was proposed by Ali *et al.* (2016). The microfluidic device provides a high sensitivity of 683.3 μA mg–1 L cm^{-2}, a wide dynamic range from 0.01 to 442 mg L^{-1} cm^{-2} and an ultralow limit of detection of 0.01 mg L^{-1} for nitrate ions in real soil sample solutions. Soil diseases were diagnosed through quantitative measurement of differential oxygen consumption between good and bad microbes resident in the soil (Rai *et al.,* 2012). Dorji *et al.* (2017) introduced a portable electronic nose (e-nose) wireless sensing station for online soil monitoring. Volatile organic compounds (VOCs) footprints obtained from the farmer's field were correlated with physical and chemical properties of the soil, thereby ensuring precise soil nutrient management.

Niguyen and Angeles (2012) determined the changes of the nitrate concentration in pineapple using nitrate strip to establish the critical values of NO_3 in sap related toNO_3 of the sap leaf and the vegetative yield. Carlson *et al.* (2000) conducted a fluorimetric biosensor experiments to quantify aflatoxins, which are commonly found in a variety of agricultural products. A high density microarray biosensor was established to detect E. coli O157:H7 colony forming units. The change in impedance of the biosensor is proportional to the number of bacteria on the sensor surface (Radke and Alocilja, 2005). A simple and sensitive dual amplified electrochemical immunoassay was developed using gold nanoparticle and horseradish peroxidase (HRP) for the control of Stewarts vascular wilt of maize with a limit of detection (LOD) of 7.8 103 cfu/mL. HRP method of identification increased the detection sensitivity by 20-fold compared with conventional ELISA (Zhao *et al.,* 2014). An Impedimetric platform based biosensor was developed for the detection of Prunus Necrotic Ringspot Virus (PNRSV) in plant extracts using anti-PNRSV IgG polyclonal antibody, which is capable to discriminate healthy plants from infected plants (Jarocka *et al.,* 2013). Similarly Lau *et al.* (2017) presented a new recombinase polymerase amplification (RPA) based isothermal electrochemical biosensor for plant pathogen DNA detection, which was composed of colloidal gold nanoparticle

and disposable screen printed electrode. The developed sensor was 10,000 times more sensitive than conventional gel electrophoresis or PCR.

Xanthomonas axonopodis pv. vesicatoria bacterial spot diseases were successfully detected using Fluorescent silica nanoparticles (FSNP) conjugated antibodies Etefagh *et al.* (2013). Highly sensitive QCM and selective (quartz crystal microbalance) biosensor were introduced for the detection of maize chlorotic mottle virus (MCMV) with a detection limit of 250 µg/mL. A mixture of 1:10 11-Mercaptoundecanoic acid and 3-Mercaptopropanoic acid was applied on gold surfaces of QCM for specific recognition of MCMV and anti-MCMV (Huang *et al.,* 2014). Mendes *et al.* (2009) introduced a biosensor that can detect soyabean rust *Phakopsora pachyrhizi* which has been reported as pathogenic fungus. The acoustic-based biosensor (QCM) could sense the plant pathogens like *Ralstonia solanacearum*, *Xanthomonas campestris pv. Vesicatoria* and *Pseudomonas syringae pv tomato* (Papadakis *et al.,* 2015).

Tang *et al.* (2015) developed a simple organophosphorus detecting biosensor in Fuji apple and cucumber by utilizing unmodified screen printed silver electrode, which are characterized by thiocholine generated by acetylcholinesterase (AChE). A detection limit of 2.5 µg/L chlorpyrifos was obtained during the study. Nanomaterials like multi walled carbon nanotubes, gold, silver and graphene nanoparticles, SnO_2-chitosan, silver-graphene nanocomposite have also been used for this purpose (Charoenkitamorn *et al.,* 2015; Chen *et al.,* 2015; Chatzipetrou *et al.,* 2016 and Govindasamy *et al.,* 2017).

The potential challenges, that would arise due to increase in global population and climate change, warrant intervention of nano technolgiocal approaches in agriculture, to harness the sustainable crop production. The use of nanomaterials has been evidenced in potential applications such as nano fertilizers, nano pesticides to control emerging pest and diseases and to tackle the resistance evolution, nanomaterials to improve the quality of soil, nano biosensors for precision agriculture and packaging systems, nano technologies in waste management. However, the full potential of nano biosensors in agriculture and food sector is yet to be realized. In addition, any new technological interventions need a long term risk and impact assessment on non-targeted organisms (bees, soil microbes) and its associated environmental effects.

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