Biosensors developments and potential applications in the agricultural diagnosis sector

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Abstract

There has been a phenomenal growth in the field of biosensor development in recent years with emerging applications in a wide range of disciplines, including medical analysis, food and the environment. The increase in the number of analytes requiring monitoring and others that require control, and the need for high sensitivity, speed, and accuracy of analytical measurements have stimulated considerable interest in developing sensors as diagnostics tools. A range of molecules with biorecognition powers are available naturally such as antibodies, enzymes, cell receptors and nucleic acids and are used as the sensing receptors in biosensors. The combined approaches of computer (molecular) modelling and combinatorial synthesis or molecularly imprinted polymers are undertaken today as a new method to produce synthetic receptors that can be used in sensor development. A wide range of transducers is also feasible to fulfil the rapid monitoring needs of the diagnostic market. Biosensors can also be incorporated into simple-to-use instruments as an on-line monitoring device or a one-shot sensor. This paper deals with recent developments in biosensors and their potential use in the agricultural diagnostic market. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Recent years have seen water companies, food manufacturers and farmers under increasing pressure, both from consumers and legislation. This is to provide life essential entities, such as water, air and food which are high in quality, free from...
polluting compounds and chemical residues and accurate in nutritional value in the case of food. The increase in the number of pollutants found in soil, water sources and food, due to the large use of chemicals, poses potential hazard to human health. As a result more stringent legislation has been introduced to monitor and control the release of contaminants. Also, the demand for fresh natural foods, ready prepared, and for cook-chill food containing less preservatives and additives, more nutritional value and free from pathogenic microorganisms, has fuelled demands for rapid sensing methods.

Conventional ‘off-site’ analysis requires the samples to be sent to a laboratory for testing. These methods allow the highest accuracy of quantification and the lowest detection limits, but are expensive, time consuming and require the use of highly trained personnel. There are now many assays on the market, which promise results within 24 h, such as immunoassays, polymerase chain reaction (PCR) assays and ATP detection methods (Stephens et al., 1997). In particular, many rapid assays for microbial contamination are available (Hobson et al., 1996). Immunoassays are commonly used to measure the concentration of a variety of hormones, allergens, viruses and bacteria in a clinical laboratory. Such tests are very important in the diagnosis of BSE and cancer in cattle. There is an increasing need for more easy-to-use immunoassays. By using robust, rapid, relatively low cost technologies, sample analysis can be made at the sampling sites ‘on site’. The number of samples requiring further analysis using laboratory-based instruments can then be reduced. There is a clear need for a simpler, alternative analysis systems and preferably methods that allow real time monitoring in the field such as biosensors.

Biosensors are analytical devices incorporating a biological material, a biologically-derived material or biomimic as the recognition molecules, utilised in conjunction with or integrated within a physicochemical transducer or transducing microsystems. These usually yield a digital electronic signal which is proportional to the concentration of a specific analyte or group of analytes. While the signal may in principle be continuous, devices can be configured to yield single measurements to meet specific market requirements. Biosensors are becoming important in a wide range of analysis. Miniaturisation, reduced cost and the improved processing power of modern microelectronics has further increased the analytical capabilities of such devices, and given them access to a wider range of applications (Newman and Turner, 1994). Different biosensor formats have been developed for single target analytes and for broad-spectrum monitoring.

The diagnostics industry is very diverse, with numerous markets requiring different products. The main controlling influences are price of the instrumentation and of the test, accuracy required, sensitivity, number of parameters required, speed and portability (Newman et al., 1998). The types of instruments required for the agro-food diagnostics market can be divided into large multi-analysers, bench-top portable instruments and one-shot disposable sensors. Many of the instrumentations developed to date were for the medical diagnostics market. However, these can be adapted for the agro-food market. In addition, the market for diagnostics continues to grow; for example, over 10 million penicillin assays are performed on the milk of 12 million cattle in U.S. dairy farms each year (Suleiman and Guilbault,
1994). Fish and meat freshness instruments, based on the determination of nucleotide-related compounds, to indicate whether the product is fit for human consumption, have been introduced to the market (Tothill and Turner, 1998). A staggering diversity of research on biosensors is reported in the literature and offers a seemingly infinite number of biosensor possibilities, but most of this research has been concentrated on small niche applications.

2. The receptor molecules

The selective binding capabilities inherent in biomolecules have been exploited in biosensor devices. Most biological components have recognition properties, which can be applied to produce either an affinity or a catalytic sensor. A diverse range of naturally produced molecules such as nucleic acids, protein lipids and their derivatives, enzymes, antibodies, cell receptors etc. can all be used as the sensing element in biosensors. New advances in receptor discovery such as the development of artificial receptors using a combined approach of computer (molecular) modelling and molecularly imprinted polymer (MIP) or combinatorial synthesis has increased the range of receptors that can be used for the construction of suitable sensing layers for biosensors. In catalytic sensors, the change in the concentration of a component resulting from the catalysed reaction is detected to give the sensor signal. In the case of an affinity sensor, the binding event itself between the receptor and the target analyte is monitored.

A large number of biochemical reactions are catalysed by specific enzymes. Enzymes are used extensively in biosensors as the catalytic component. However, the most important group has been the oxidoreductases, catalysing oxidation or reduction events using either oxygen or cofactors. Enzymes are either used alone, as in catalytic biosensors or alternatively, they are used in conjunction with other components, such as antibodies as the marker where they can form a signal amplifier. Many enzymes are unsuitable for use in such devices due to their lack of stability and enzyme modification or other means of improving stability is desirable (Newman et al., 1998). The routes for achieving this are many, and include chemical stabilisation, immobilisation procedures that confer stability and acquiring enzymes from different sources such as thermophilic organisms.

Whole-cells of living organisms, such as bacteria, yeast, fungi, plant and animal cells or even tissue slices have also been used as the recognition component by interrogating their general metabolic status. This usually involves detecting oxygen or substrate consumption, the production of carbon dioxide or metabolites, detecting of bacterial luminescence or direct electrochemical sampling of the electron transport chain (Tothill and Turner, 1996).

Affinity sensors use mainly antibody-antigen binding reactions, but other biological components such as cell receptors, single-stranded DNA (to bind and detect its complementary sequence) and lectins (plant proteins used to bind carbohydrates) have also been used. Combinations of the above biological component have been utilised to provide new or improved analytical capabilities (Tothill and Turner,
The developments of polyclonal antibodies (Pabs) and the huge advances in monoclonal antibodies (Mabs) production has created a major force to be used in the diagnostics market. Mabs are widely applied in a range of devices from rapid wet chemistry assays such as immunoassay kits, to dipsticks and biosensors. The use of antibody fragments and molecularly engineered antibodies is the future area of growth in immunosensors. A new research approach is to recover the genes of useful antibodies, express them in bacteria or plants, develop 3-dimensional structural models and then derive improved variants by directed and combinatorial mutagenesis. The produced recombinant antibody’s affinity and selectivity may be changed to make it more suitable analytical tool.

The poor stability of biological molecules is often the stumbling block preventing biosensor commercialisation. Research in improving the stability of these compounds is expanding and methods such as the use of soluble, positively-charged polymers, such as diethyl amino ethyl (DEAE) dextran, lactitol, and sugar derivatives are being tested. A new approach to overcome the stability problem of biological molecules is to use artificial receptors or biomimics. Research activity in this area has increased in the last few years, in particular the production of synthetic receptors for environmental diagnostics (Bestetti et al., 1997). The development of artificial receptors for various purposes remains an important challenge. Combinatorial synthesis is one of the most exciting and rapidly growing areas in ligand discovery, which can overcome the stability problems inherent in natural ligands. However, the challenge is to produce receptors with high affinity to give the required detection limit.

### 3. Transducers and sensor fabrication

Four major types of transducers are used in biosensor devices: electrochemical (electrodes), optical (optrodes), mass (piezoelectric or surface acoustic wave devices) and calorimetric (thermistor or heat sensitive sensors). Considerable work is being carried out to improve the transducer designs, with the mergers of different technologies. Electrochemical devices usually monitor the current at a fixed voltage (amperometry), the voltage at zero current (potentiometry), or measure conductivity or impedance changes. Impedance is the total electrical resistance to the flow of an alternating current being passed through a given medium. Typically during measurement impedance decreases while conductivity and capacitance increase. Optical transducers use a number of principles, such as the effect of the biological event on light absorption, fluorescence, refractive index or other optical parameters (Tothill and Turner, 1998). Thermometric devices operate by measuring enthalpy changes during the biological reaction. Sensors based on piezoelectric principles use the change in the resonant frequency of wave propagation through a piezoelectric material. These principles can be used to measure mass, viscosity or density changes at the sensor surface. Further information on transducers used in biosensor devices can be acquired from (Kress-Rogers, 1997).
The importance of automated manufacturing technologies has been clearly demonstrated in the commercial production of devices such as the ExacTech blood glucose biosensor (MediSense, Inc., Cambridge, MA), where large numbers of inexpensive, reproducible electrochemical devices are required. The ability to print materials at high precision and speed is very desirable for the mass production of analytical devices such as biosensors (Newman et al., 1995; White et al., 1996). Several techniques such as screen-printing, ink-jet printing, air-brush and Cavro deposition have been developed, under microprocessor control and adapted for biosensor fabrication, especially thick-film biosensors. These deposition techniques are rapid and flexible with regard to the ink characteristics employed. Thin-film deposition has also been used, which involves the application of material through a mask, under vacuum, via evaporation due to heating, or by placing the substrate to be coated between two electrodes (sputtering). This process is able to create patterns less than 1 \( \mu \text{m} \) thick, making it suitable for the construction of microsensors. Thin-film sensors are generally produced by a variety of vapour deposition techniques, electrochemical methods and more recently by the use of Langmuir–Blodgett technology. Thin metallic films, usually deposited by vapour deposition have been used extensively for the production of sensors utilising surface plasmon resonance. These sensors have been primarily directed towards affinity sensing (Newman and Turner, 1994).

Silicon fabrication technology has been proffered as a means of mass production of biosensors. This is an area of intense research activity mainly by diagnostics companies. The use of silicon microfabrication for both electrochemical and optical sensors is expanding and the capability of on-chip electronic signal amplification and data processing are very attractive. Bookham Technology (Oxfordshire, UK) is using microelectronics technology based on silicon to produce optical chips for biosensor application.

4. Biocatalytic sensors

Electrochemical biocatalytic sensors have dominated the biosensor market for many years. Most of these types of sensors are based on enzyme catalysis or whole-cell sensors. An enzyme specific for the substrate of interest is immobilised on the sensor surface. The substrate is catalysed as it enters the enzyme layer, and the resulting current is proportional to the concentration of the substrate. The simplest biosensor approach is to measure amperometrically the oxygen depletion or hydrogen peroxide production associated with the reactions involving oxidase enzymes. The combination of simplicity, ease of manufacture, high sensitivity, availability and low cost of instrumentation is highly attractive. Most of the developments of biosensors have been in the field of medicine, the food industry (Issert et al., 1997) and more recently in environmental monitoring (Dennison and Turner, 1995; Marco and Barcelo, 1996). Biosensors based on the use of redox mediators to shuttle the electrons, resulting from the catalytic oxidation or reduction of the substrate of interest, to the electrode has been an area of great interest.
to many researchers. Much of the work is centred on the use of redox mediator compounds (such as ferrocene, tetrathiafulvalene, and tetracyano quino dimethane) and their derivatives (Cardosi and Turner, 1990). Careful selection of the mediator can also eliminate interference problems from other substances in the sample. There are several biosensor products on the market based on amperometric transduction, including the MediSense Blood Glucose Analyser for medical application and the Yellow Springs biosensor systems (YSI, Ohio, USA) developed for food analysis and bioprocess control. The YSI 2700 SELECT™ Biochemistry Analyser (Fig. 1) can be used for on-line fermentation monitoring or off-line sample analysis for food and drink fermentation. The biosensor system can provide nutrients and bioproducts analysis including glucose, L-lactate, L-glutamine, L-glutamate, ethanol, lactose, sucrose, galactose and methanol. Single and multi analytes biosensors based on the same principle are being developed for a diverse range of applications in the food industry.

Enzyme inhibition sensors are the most commonly reported enzyme-based biosensors for the detection of toxic compounds and heavy metal ions. These

![Image](image1.jpg)

![Image](image2.jpg)

Fig. 1. YSI 2700 SELECT™ Biochemical Analyzer: a) the biosensor principle; b) the instrument (Photo courtesy of YSI incorporated, USA).
sensors are based on the selective inhibition of specific enzymes by classes of compounds, or by the more general inhibition of enzyme activity. Most of the research carried out has been directed towards the organophosphorous and carbamate insecticides and the triazine herbicides. Several enzymes have been used in inhibition sensors for pesticides and heavy metal analysis using water, soil and food samples. These include choline esterase, horse radish peroxidase, polyphenol oxidase, urease, and aldehyde dehydrogenase (Wittmann et al., 1997). Organic phase enzyme electrodes (OPEEs) have been used for the analysis of compounds such as cholesterol, alcohols, organic peroxides and phenols. This technique has the advantages of ease of sample preparation from materials such as fats and oils and also increased enzyme stability (Iwuoha et al., 1997). Enzyme biosensors have also been widely applied to the detection of phenolic compounds (Dennison et al., 1995). These aromatic compounds are the result of production of drugs, dyes and anti-oxidants and also from the paper and pulp industry. The main enzymes used in biosensor development for this type of compounds are phenol oxidases (tyrosinases), laccases and peroxidases.

Whole cell biosensors have been utilised for environmental monitoring, exploiting the broad sensitivity of such devices to a wide range of toxins. A whole-cell biosensor contains living organisms, such as bacteria, yeast, fungi or other plants or animal cells. Biosensors based on the use of whole cells as the sensing layer generally exhibit multi-receptor behaviour but can offer increased stability when compared with enzyme-based sensors. A range of biosensors based on this principle have been developed, in particular for water monitoring (Tothill and Turner, 1996).

Biosensors for specific aspects of toxicity, such as BOD (biochemical oxygen demand), have been developed. Sensors such as the ARAS BOD Biosensor System (Dr Bruno Lange GMBH, Dusseldorf, Germany) and BOD module biosensor produced by (Prufgerate-Werk Medigen, Germany) are commercially available.

Electrochemical sensor approaches to hygiene monitoring based on the metabolism of living cells have also been commercialised. The Bactometer (Bactomatic Inc., Princeton, USA) and the Malthus 2000 (Malthus Inc., Stoke-on-Trent, UK) use impedance and conductance, respectively, to plot bacterial growth. A more rapid approach is the use of amperometry. The method comprises the use of mediators to detect the metabolic activity of the cells and the resulting current can be related to the numbers of organism present in the sample. Potentiometric approaches have also been widely investigated for the construction of biosensors, primarily using ion-selective electrodes (ISEs). However, potentiometric enzyme-based devices are particularly prone to interference from pH changes and also drift due to critical dependence on the reference measurement (Tothill and Turner, 1998). Optical biocatalytic sensors have been developed based on the use of a fluorescent dye and its interaction with an immobilised enzyme. Optical sensors are usually based on optical fibres or planar wave-guide films. Based on a pH optode, different fibre optic biosensors have been constructed for glucose, urea, penicillin and creatinine analysis (Mueller et al., 1995). Current commercial examples, such as Optical Sensors Inc. (MN, USA) fibre optical sensors for the measurement of blood pH and dissolved oxygen and carbon dioxide concentrations, can be mainly found
in the medical area. The transfer of these technologies to the agro-food and environmental sector can be anticipated in the near future (Stephens et al., 1997).

5. Affinity sensors

Phenomenal growth in affinity sensor research and development has been undertaken in recent years. By utilising the immunorecognition properties of antibodies in immunosensors and affinity sensors the range of analytes that can be diagnosed has been broadened. The use of antibodies in various immunosensor configuration has also been applied in a wide range of applications and have been reviewed by many authors (Hock, 1997; Skladal, 1997; Ghindilis et al., 1998). Immunosensors offer a wide range of potential applications to the food industry, water companies, and regulatory authorities. For an immunosensor or immunoprobe, the antibody (Ab) or the antigen (Ag) constitutes the bio-specific component in the sensor structure. Many immunosensors have been developed and with minor adaptation these can replace immunoassays. At present immunodiagnostic tests are used in pollution detection in food and water samples and also on-farm monitoring of livestock reproduction (milk progesterone), and quality control of foodstuffs originating from livestock production (authenticity and adulteration testing). These tests can be developed to a new generation of rapid immunosensors for real-time and on-site applications. A range of research projects has been undertaken to develop immunosensors for residues in food (antibiotics, toxins, and pesticides), the presence of additives and hormones. However, the availability of the required antibody can limit the potential for diverse analyte detection by immunosensors. Increased research in the development of specifically tailored antibodies such as plantibodies produced in plants, recombinant antibodies, catalytic antibodies or abzymes, artificial receptors and molecularly imprinted polymers should overcome this problem (Turner, 1997).

Detection by electrochemical immunosensors is generally relay on the use of electroactive labels, usually based on enzyme labelling and amplification techniques. The sensors can be inexpensive, and may achieve very low detection limits (1 ppb). Different types of electrochemical immunosensors and affinity sensors have been developed for environmental analysis using different transducers (Marco et al., 1995; Setford et al., 1999). The scientific literature is increasingly reporting development of one-shot disposable immunosensors or on-line immunosensors for a diverse range of analytes (Baumner and Schmid, 1998; Bilitewski, 1998; Santandreu et al., 1998; Vianello et al., 1998). However, the technology required to produce these types of sensors has not yet reached the level of development needed and is very much still at the discovery stage.

Immunosensors can be divided into classes depending on the transducer technology employed. In the field of affinity sensors, optical devices have a clear advantage over electrochemical methods due to their ability to monitor binding reactions directly. The major drawback to the application of optics to chemical sensor applications remains the high cost of many optical components, but these costs are
constantly falling. Optical techniques such as surface plasmon resonance (SPR) and evanescent wave (EW) have shown promise in providing direct measurement of antigen (Ag)–antibody (Ab) interactions occurring at the surface-solution interface, the surface usually consisting of a glass prism on a gold or silver metal layer. SPR is a phenomenon which occurs when a beam of light is directed onto a glass-metal interface, which results in changes in the resonance angle (Cullen and Lowe, 1990). The BIAcore™ biosensor system based on SPR technology was developed by Pharmacia (Uppsala, Sweden) and now commercially available, represents a significant breakthrough in immunosensor technology. BIA technology enables detection of biomolecules in real time without the use of labels. However, the instruments are expensive and are mainly laboratory based and require trained personnel to interpret the results. The Pharmacia Biacore™ biosensor has been reported to detect atrazine indirectly at 0.05 µg L⁻¹. Recently, BIAcore AB have launched the BIAcoreQuant™, a version of their SPR technology for the automated analysis of vitamins in foods (Fig. 2). The assay is designed as an inhibition assay and similar principles are applied for the determination of drug residues in meat and milk products using BIACORE 2000.

Amersham International plc is another company which has, in the past, been active in research into SPR-based immunosensors for infectious diseases and have developed SPR-based immunotechnology which employs antibodies labelled with latex particles (beads). The beads amplify the change in refractive index at the sensor surface-solution interface which occurs when the antibodies bind to the immobilized antigen layer and thus cause a large change in the resonance angle (Hobson et al., 1996). A fluorescence-based EW immunosensor that incorporates a novel capillary fill design has been developed by Serono Diagnostics (Woking, UK). The system consists of two glass plates separated by a narrow capillary gap of ~100 µm. The lower plate acts as an optical waveguide and contains on its surface an immobilized layer of antibodies. This sensor benefits from the capillary fill system which draws a fixed volume of sample into the space between the plates, regardless of bulk sample volume (Hobson et al., 1996). Affinity Sensors (Cambridge, UK) has created a new generation of EW sensors, resulting in the development of the IAsys technology. This advanced optical biosensor system (IAsys and IAsys Auto +) also enables analysis of the biomolecular interaction in real-time. Reusable cuvettes offer a choice of derivatized sensor surfaces and chemistries. The ligand is simply and efficiently immobilized onto the sensor surface and binding of the analyte can be detected immediately.

Piezoelectric transduction approaches and in particular surface acoustic wave (SAW) devices have gained attention recently. Piezoelectric materials (usually quartz crystals) that may be brought into resonance by application of an external alternating electric field. The frequency of the resulting oscillation is determined by the mass of the crystal. The principle attraction of piezoelectric-immunosensors is their ability to monitor directly the binding of Ab-Ag reaction encountered in affinity sensing. However, these devices have a low sensitivity for small molecules.

Immunosensors may not have commercial devices developed specifically for the diagnosis in the agro-food and environmental domains, but their long-term devel-
The development potential is promising. The development of disposable electrochemical affinity sensors for the rapid detection of residues of anabolically active illegal androgens, antibiotics and other residual compounds in food samples will allow regulatory bodies to improve their screening programme. A potential market for immunosensors is genetically modified foods testing (GM) for protein analysis. Immunoassay tests as a plate test or dip-stick devices for the detection of GM foods in plant tissues, raw agricultural commodities and also food ingredients are marketed to day by SDI Europe Ltd. (Hants, UK). These types of tests can be developed into immunosensors devices.
6. DNA biosensors

There have been huge advances in the development of DNA biosensors. Since nucleic acids, the building blocks of DNA and RNA, are universally present in all living cells they can be used as a general indicator of microbial biomass. The polymerase chain reaction (PCR), is a widely used method for amplifying trace amounts of DNA for analysis. To date, it has been mainly used for qualitative analysis, but the need for quantitative information has resulted in further development of PCR protocols (Warren et al., 1991). Quantitative PCR methods are shown to be extremely sensitive, and fully automated detection systems which should be rapid, simple to use and inexpensive are being developed.

DNA biosensors are currently used in the detection of infectious diseases and the genetic abnormalities. The main approach has been by the use of immuno-based sensors. This technology is well established and the performance of these tests is good. PCR is widely used to amplify the signal in DNA probes, but it is time consuming. There is intense current interest in microsystems for DNA analysis. An electrochemical DNA sensor based on a gold electrode modified with DNA probes and an electroactive hybridisation indicator has been reported in the literature (Hashimoto et al., 1994). A range of detection systems have also been applied in DNA probes such as the use of enzyme label, an SPR-based biosensor (Nilsson et al., 1995), an evanescent wave biosensor (Pandey and Weetall, 1995) and an acoustic based sensor (Andle et al., 1995).

Affymetrix (USA), has developed a platform for acquiring, analysing and managing complex genetic information. The system is based on disposable DNA probe arrays (GeneChip) containing selected gene sequences on a chip, and an instrument to process the chips, and analyse the information. This ‘lab-on-a-chip’ offers traditional, laboratory-based biological assays in convenient on-site or on-line instruments. DNA chips are used for microorganisms identification or detection of genetically-modified foods (GM foods). The company is developing new chips for microbial contamination diagnosis in environmental samples.

GeneScan Europe (Hanse Analytik GmbH, Germany), markets test kits for the detection of genetically modified components in human and animal foods by DNA analysis using PCR techniques. These tests can also be developed in to DNA biosensor devices.

7. Electronic noses

Electronic noses are based on the use of artificial receptors in the sensor array. Although, these types of instruments can only be classified as affinity sensors to date their emerging importance in food analysis justifies their inclusion in this article. There has been a great deal of research in the development of the electronic nose in recent years (Gibson et al., 1997; Keshri et al., 1998) with a diverse range of applications. This type of sensor instrument mimics the olfactory system in the nose (Pearce, 1997). The instrument consists of the sensor array, the circuitry
represents the conversion of the chemical reactions on the sensor to electrical signals and the software which analyses the signal by pattern recognition methods, such as principal component analysis (PCA), discriminant function analysis (DFA), cluster analysis and artificial neural networks (ANN). The results are comparative rather than quantitative ‘fingerprint’. A variety of sensors are used ranging from metal oxides to conducting polymers. The polymers can be highly sensitive but not specific and can respond to volatile compounds with molecular weight ranging from 30 to 300 (Reineccius, 1996). Molecules such as alcohols, ketones, fatty acids and esters give strong response, while fully oxidised species, such as CO₂, NO₂ and H₂O have a lower response. The sensor array can also recognise molecules containing sulphur and amine groups. The electronic noses have been used in the medical, environmental and food diagnosis. The majority of the current research concentrates on quality control in the foods and drinks industry, such as detection of microbial contamination (bacteria, fungi and yeast) and authenticity (beverages, coffee and meat) (Anklam et al., 1998; Eklov et al., 1998; Keshri et al., 1998).

8. Conclusions

The diagnostics market is expanding rapidly and covers a wide range of disciplines. The establishment of appropriate technologies to apply biosensors to practical agriculture and horticulture is expected to produce a significant effect on quality improvement and cost-reduction in this area. The application of biosensors in the medical diagnostics market has been highly successful. However, their potential success in the food, agriculture, veterinary diagnosis and environmental market is still to be established. Biosensor systems which are relatively small, portable instruments, have an on-site application and relatively inexpensive are desirable in the agro: food analysis. A vast amount of research is being undertaken in diagnostics companies and research institutions to develop biosensor technologies for the agricultural diagnosis sector. However, moving the technology to the marketplace faces many challenges. For a developed biosensor to be successful it must compete with the fairly well established chemical, DNA and immunoassays techniques. The future holds much promise, but lies in addressing niche markets and changing requirements in complex systems.

References


