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Review Article

Biosensor: Potential and Scope in Agriculture

Subhadeep Mandal and Ganesh Chandra Banik*

Department of Soil Science and Agricultural Chemistry, Uttar Banga Krishi Viswavidyalaya, Pundibari, Cooch Behar-736 165, West Bengal, India

Abstract

Ensuring food safety and quality control for agricultural produce are clearly necessary, especially for third world countries. Biosensor opens up the opportunity to solve out this problem with higher accuracy, portability and sensitivity over conventional measures. In-situ analyses of fertilizer management, soil and water quality detection, pesticide residue measurement and waste water monitoring are some of the important aspects for crop growing and hence for ensuring food security. Over time, integration of biosensors with nanotech stimulated the sensing mechanism with a wide range of transducer line-up. Improvisation in processing algorithm with artificial neural network (ANN) opened up opportunities for multi-analyte detection. Further challenges in development and agricultural market creation for commercial use of biosensors are also addressed in this review.

Keywords: Agricultural market, Algorithm, Biosensors, Food safety, Nanotech

***Correspondence**
Author: G. C. Banik
Email: gcbanik79@yahoo.co.in

Introduction

Biosensor development set sail as an interdisciplinary analytical tool for assessing food safety, quality control, environment impact assessment (EIA) with agricultural, medical and industrial applications. To feed about 9.1 billion people in 2050, an estimated overall rise of 70% food production between 2005/07 and 2050 is required; whereas for developing countries, production needs to be almost doubled [1]. Factors like climate change and industrial globalization are the emerging threats for food safety. Rapid change in food-web due to environmental contamination is significantly affecting the path of food from field to plate. Biosensor technology started to popularize with its ability to rapid on-site detection with lower investment whilst conventional off-site analyses bounded by time, high cost and inadequacy of trained personnel. Although, years after discovery even being a potent analytical tool till now transfer of technology (TOT) to agricultural market is limited. Agri-industry is a growing sector with expanding market place. Cost and necessity of multi-analyzers are so high in agricultural domain, but major capital investment and resource involvement are restricted to biomedical sectors only. Biosensor global market for food safety is projected to reach from 17 billion dollars in 2018 to 24.6 billion dollars in 2023 [2]. Biosensors need to be diversified in near future addressing towards agriculture, entangled with its various disciplines.

Principle of biosensor

Biosensor is an analytical device that incorporates biological sensing elements (bio-receptors) that either closely connected to, or integrated within, a transducer system (**Figure 1**). Biosensor development started with development of enzyme based electrodes for glucose estimation by the American biochemist Dr. Leland C. Clark Jr. in 1962. However, he developed the first 'true' biosensor (Clark electrode) in 1956 for detection of oxygen in blood water and liquid. He is known as 'Father of biosensors', however, the term 'Biosensor' was coined by Karl Cammann in 1972.

The technology converts biologically induced recognition event into a detectable signal (transduction) and readings are obtained on screen after a series of processing [4]. The principle of detection broadly divided into five steps: a) *Immobilization of bioreceptors* on transducer surface to make the overall process efficient and cheaper; b) *Surface treatment to transducer* Surface treatments needs to be done to link biological components covalently with reactive free groups with the treating agents; c) *Specific interaction of analyte* of interest to the complementary bio recognition element results in single/multiple physico-chemical changes (pH, redox reactions, specific ion exchange, mass and heat transfer, gaseous exchange etc.) close to the transducer surface; d) *Conversion of biological signal* generated from physico-chemical changes and transducer converts into the electrical signals. This electronic signal is proportional in magnitude or frequency to the concentration of a specific analyte, to which the biosensing element binds [5]; and e) *Amplification of small signal (electrical signal)* by the amplifier before it fed into the microprocessor followed by signal processing, interpretation and displaying result. Depending on transducer types biosensors can be classified as [6] - electrochemical biosensors (conductometric, potentiometric), optical biosensors (interferometric, colorimetric), mass-based biosensors (piezoelectric, acoustic wave), calorimetric biosensors etc.

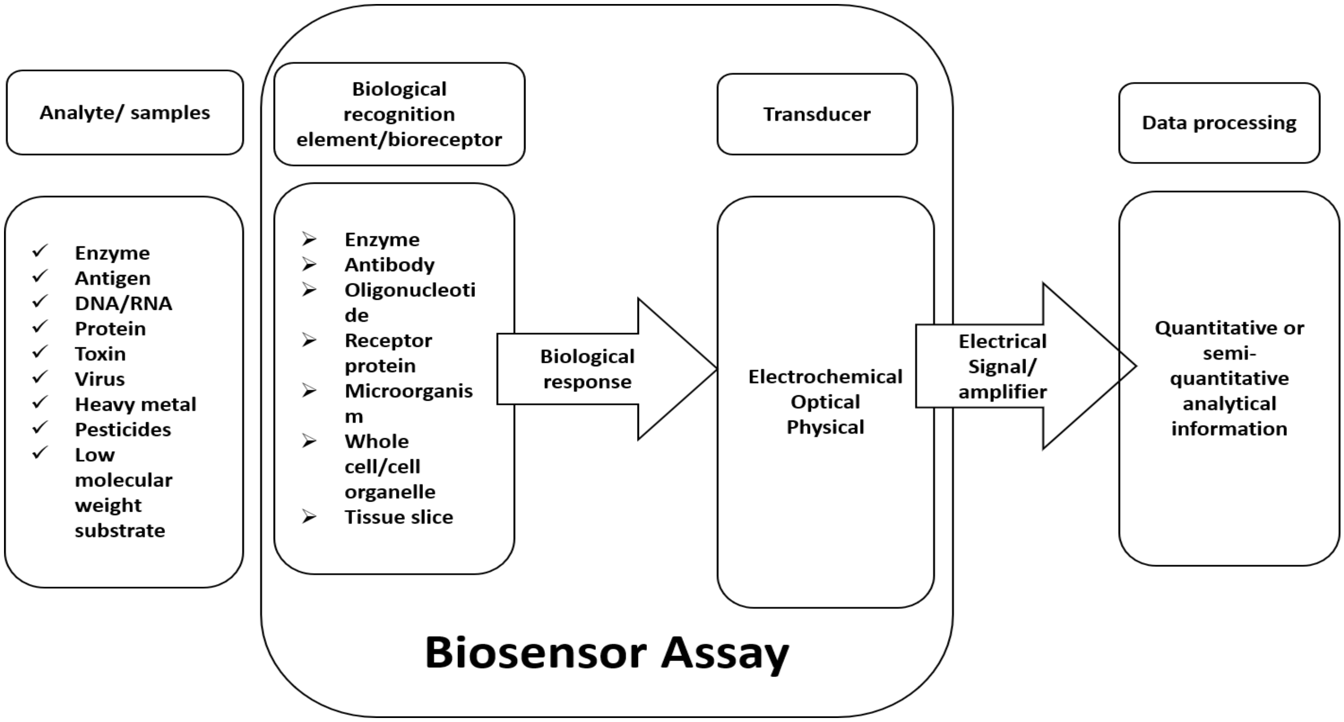

Figure 1 Principle of operating a biosensor and main components [3]

Types and potential use of biosensors

Agriculture sector is a potential field for technological interventions of biosensors. Biosensors can be broadly classified [7, 8] and presented in **Table 1**.

Nanobiosensor: integration with nanotech

Nanoparticles exert highly different physico-chemical properties from the same material at the bulk scale, like- high reactivity to target surface etc. Nanobiosensors are made up of nanomaterials at scale of 1 to 100 nm. Nanoelectromechanical system (NEMS) is developed as an advanced signal processing and transduction system using nanocoatings to transducer surface. Amongst different nanoforms, like-nanotubes, nanowires, nanorods, nanofilms [31], the nanoparticles were best studied and analysed till date. The nanobiosensors have been designed by integrating nanoscience, electronics, computers and biology which have an extraordinary sensing capacity. The nanobiosensors can also be integrated with other technologies like lab-on-a-chip for the molecular analysis. These integrated biosensors can effectively be used to analyze urea, glucose, pesticides etc. and also for detection the presence of various microorganisms including pathogens [32].

Application in agriculture

Linking with nanofertilizers: an agent to promote sustainable agriculture

Nanofertilizer application emerged as a potential nutrient delivery system that exploits nano-domains of plant parts for efficient nutrient targeting encapsulated within a nanoparticle. Biosensors can effectively be attached to the nanofertilizer for selective and sustained nutrient release over long time based on agro-climatic conditions. Zeolites are naturally occurring crystalline aluminum silicates with high retention capacity among others. Zeolite treated transducer can be used to sense the nutrient deficiency in either plant or soil system and can control the release of water and/or nutrients retained in the zeolite [32]. That means either less fertilizer or the same amount of fertilizer lasting longer can be used to procure for same amount of yield. Zeolite has further added benefits as unlike other soil amendments that it does not break down over time in soil but remains longer to help to improve nutrient and water retention. Typical response of biosensor was also demonstrated based on adsorption of urease enzyme on Nanozeolites by successive additions of urea (0.1 mM) [33].

Table 1 Biosensor materials and their potential applications

Transducer type	Biosensor type	Principle	Application
Electrochemical	Potentiometric	Measures electric potential	Urea [9], CO_2, pesticide, sugar, pH determination [10]
	Conductometric	Change in conductance	Environmental contamination [11], pesticide [12], and heavy metal [13] detection
	Amperometric	Electron movement due to redox reactions	Organophosphate pesticide [14], pathogen detection [15]
	Impedimetric	Measure impedance of an electrochemical cell	Peptide, small protein [16], milk toxin [13], and food borne pathogen detection [17]
Optical	Bioluminescent	Change in luminescence	Heavy metal detection [18], food toxicant, pathogen study [19]
	Fluorescence	Reaction with fluorescence tagged biomolecules	BOD measurement, water availability to plants, pathogen detection [20, 21]
	Colorimetric	Change in optical density	Water and food borne pathogen detection [22, 23]
	Surface Plasmon Resonance (SPR)	Change in refractive index from binding of bioanalytes	Livestock, disease diagnosis, drug residue testing, toxic gas monitoring [24]
Piezoelectric	Quartz Crystal Microbalance (QCM), Surface Acoustic Wave (SAW)	Mass change in bio-components	Humidity sensor [25], food safety [26], organophosphate and carbamate pesticide detection [27], glucose monitoring [28]
Thermal	Calorimetric	Heat release and absorption	Organophosphate pesticide [29], water and food pathogen detection [30]

Diagnostic tool for soil quality and disease assessment

The Research Center of Advanced Bionics (RCAB), Japan claimed to develop world's first biosensor for soil diagnosis aimed at quantification of soil properties based on soil microbes. The basic principle lies in quantitative measurement of differential oxygen consumption in respiration or relative activity of 'good microbes' and 'bad microbes' in the soil. A dual sensor system was developed that measures microbial respiration of two different strains simultaneously, immobilized on different transducer system and is proportional to the decrease in dissolved oxygen (DO) when dipped in soil extract [34]. Eventually, disease symptoms can be estimated with ratio response to obtain a correlation matrix. The findings are directed towards rapid prediction of disease outbreak with emphasis on numerical database rather than based on results with long term experiments.

Pesticide residue determination

Pesticides analyses by high performance liquid chromatography (HPLC) or gas chromatography (GC) require laborious extraction and clean up steps that increase analysis time and also the risk of analytical and human errors. Cost of carbamate analysis with a biosensor is also much lower compared to chromatographic methods [35]. Biosensors generally measure the correlation between increase in toxicity of a certain pesticide and a decrease in the activity of a biomarker such as an enzyme. Enzyme based biosensors have rapid regeneration activity, an incubation time of only ten minutes before addition of the substrate. This activity can effectively be registered by employing different types of transducers for detection of different substrates or products of enzymatic reactions. pH sensitive transducer can be used in AchE-based biosensors to relate amount of choline generated to enzymatic activity based on inhibitory action of organophosphorus and carbamate insecticides [33]. Fibre optics based biosensors is used to determine pesticides propoxur and carbaryl, where pH sensitivity can be accessed via change in reflectance at 602 nm [36]. Recently, nanopesticide development that can be released with environmental trigger is initiated [37].

Water quality monitoring and electricity generation

The presence of large consortium of enzymes makes microbial biosensors highly stable and sensitive to a large variety of analytes as it is a ‘whole cell’ [38] rather than a single bioactive molecule. Microbial fuel cells (MFC’s) are devices that directly convert the chemical energy in organic matter into electricity via metabolic processes of microorganisms [39]. Here, anode surface is associated with biofilms of anodophiles microbes. Electrons generated by oxidation of biodegradable organic molecules in anode are extracellularly transferred to cathode thus producing electricity. Thus, MFC technology is highly functional regarding treating wastewater whilst generating electricity. Based on different organic functional groups (acetate, propionate, butyrate group) in water, the interpretation is made [39, 40]. Diversified microbes that can survive under harsh conditions can be effectively used in water monitoring and industrial agricultural waste monitoring. Another benefit of MFC technology is measuring biological oxygen demand (BOD) [41], pollution status and measuring organic carbon content (indirect) [42] at the same time. The sensor showed stable performance for five years without particular maintenance with a response time of 2.8 minutes with a single chamber device. This can potentially substitute BOD_5 test that requires at least five days of incubation period.

Advantages and disadvantages of biosensors

Biosensors are portable, highly stable, relatively inexpensive and posses a wide linear range of sensor response [43]. With higher selectivity towards targeted ions [44] and ppb level detection, sensor based response eliminates the cost of onsite monitoring associated with collecting, isolating, packaging and transporting the sample to be analyzed. As a potential go-to technology it does have certain disadvantages that need to be addressed. No heat sterilization (denature the biological part of the biosensor), high cost of development, lower stability of enzymes and antibodies, lack of reproducibility, lack of reusability, cell intoxication etc. are some of the constraints discussed in literature. Troubleshooting of disadvantages is emphasized by several authors from various disciplines. But as a multidisciplinary approach, it needs a common platform to reach at an augmented solution [45].

Market assessment, risks and acceptance

Nanomaterials are probably beneficial with contrasting opinions, but the primary concern is associated with higher reactivity with precision targeting. Moreover, minimal funding for risk assessments led this approach obstructive in this research arena. The latent risks of widespread and increasing use of engineered nanomaterials for factors like toxicity, bioaccumulation, exposure risk for environment and/or human health has raised concerns. Expertise should be accessible by proper characterization of sensor prototypes in biological environments. The risk factors with commercialization are concerned to pose “*negative economic effects on the poor by increasing productivity in developed countries*” [46] which may decrease commodity prices in developing and poor countries. Besides, marketing of any product depends on the public acceptance of the same. Till date, consumers lean to be more unwilling to nanobiosensors applications and don’t perceive all products with same risk levels. One of the probable solutions is to proper labelling on nano-products in certain developed countries which might lead to technology consumption and regulations in developing countries. However, market creation is consumer driven and necessarily need sophisticated government intervention for decentralization of technology to the farmers. At grass root level focus must directed towards human resource development with an acceptable turnover. Sensing need to be popularized with handheld proximal gadgets, just like smartphones, with a centralised server based ecosystem. The initiative should be looked into as a low-cost basic intensive data input approach, which can be calibrated and modulated at hierarchical levels.

Future scope and research

Commercial exposure essentially expands future scope. Transducer hardware can be upgraded with ‘carbon’ nano architecture resulting improved electrochemical signal transduction. Quantam Dot method is another fast growing technology where fluorescent nanocrystals are used as semiconductor to measure pathogens in water [47]. In remote sensing, solely ‘physical’ based proximal sensing cannot justify the risk bearing ability of a productive system. Hyperspectral sensors can be equipped with bio-molecules to enhance sensitivity and minimize error towards sensing. As an improved input for data mining techniques (ANN), in-situ acquisition of bio-chemical properties of leaf along with spectra has a tremendous potential to boost up predictive modelling.

Conclusion

Biosensor is an emerging and promising technology; however there are some technological obstacles that need to be overcome. Till now, biosensor approach is more of a sophisticated biomedical research tool rather than agricultural needs. The establishment of appropriate technologies to apply biosensors to practical agriculture is expected to produce a significant effect on quality improvement and cost-reduction in this area. Advances in areas such as surface chemical analysis, stabilisation, and automated manufacturing technologies would widen the market and allow biosensors to be more competitive in the agricultural market. However, moving the technology to the market place faces many challenges which must be properly dealt with.

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