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REVIEW ARTICLE

New-age frontiers in enhancing the mobility of cell-based biosensors using drone technology

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Abstract

The application of cell-based biosensor technology has emerged as a cutting-edge tool in the domains of food safety, environmental monitoring and pharmaceutical research. These biosensors operate by detecting changes in cellular proliferation, gene expression and metabolic activity in response to environmental stimuli. They also play a promising role in the detection and recognition of infectious diseases in crops and livestock, *in situ* analysis of pollutants in crops and soils, real-time measurements of crucial food processing indicators, monitoring animal fertility and screening therapeutic drugs in veterinary research. Unmanned Aerial Vehicles (UAVs) offer significant potential to enhance the mobility and deployment efficiency of cell-based biosensors, enabling real-time, remote and large-scale environmental diagnostics. Various biosensor models, such as chemical, physical and optical, utilizing modified chemicals, nanomaterials, nutraceuticals and biocompatible molecules are increasingly being explored for integration into UAV platforms for applications, such as biosensing, bio-imprinting and in-field testing. This article summarizes the existing applications of bio sensors and explores the potential of bio sensors using drones, highlighting research directions aimed at advancing societal welfare.

Keywords: agriculture and allied agriculture; cell biosensors; health sectors; nanomaterials; Unmanned Aerial Vehicles (UAVs)

Introduction

Recent scientific and industrial developments have significantly advanced technologies aimed at improving quality of life. Among these, the discovery and application of biosensors have proven a powerful engine of innovations resulting from their wide variety of applications in almost all sectors of life. Biosensors are widely used in agriculture, engineering, medicine, nanotechnology, health (blood test, diabetics and ailments diagnosis) and wastewater treatments. Compared to traditional devices, biosensors are environmentally friendly, readily available, economical, reusable, recyclable and reliable tools. For enhancing the mobility of bio sensors, automated or robotics-based technology is essential. In this context, UAVs popularly known as drones could play a vital role.

Biosensors

A biological sensor (or biosensor) is an analytical device, that incorporates a biological element integrated with a transducer system. The electronic or biomimetic sensing element may include tissue, microorganisms, antibodies, natural products, cell receptors, enzymes or nucleic acids. The transducer can be physicochemical, optical, piezoelectric, electrochemical in nature. Biosensors are classified based on their bioreceptors, such as enzymes, antibodies (immunosensors), microbes and DNA (genosensors). Additionally, there are different types of biosensors based on transducers, viz., electrochemical, optical biosensors, piezoelectric or magnetic, magneto elastic, field effect transistor (FET), calorimetric and non-invasive biosensors. Among the biosensors, electrochemical biosensors are relatively inexpensive, with a potential of miniaturization and are suitable for point-of-care testing (POCT). In recent years, several research studies have been conducted for developing inbuilt biosensor for tracking human activity, animals and barcoding of raw materials for manufactures, etc. Current research challenges include exploring diverse applications of low-cost biosensors for daily use (1).

The invention of nanomaterials such as carbon nanotubes, quantum dots and dendrimers for the application of biosensors provides opportunities for developing a new generation of biosensor technologies. These materials improve the physical, chemical, mechanical, electrochemical, optical and magnetic properties of devices, enabling the transform biosensors to high throughput biosensor arrays (2). Biological molecules can adopt novel structures beyond their native forms in nature, enabling them to detect analytes in stereoisomer-specific patterns. These biomolecules are being fabricated into multifunctional nanocomposites, nanorods, nanoclusters, nanofilms and nanoelectrodes, a technology still under development (3). Laboratory- scale processing, characterization, interference issues, limited availability of high-quality specific chemicals and process- specific tailoring to achieve customized chemical behavior of such nanoscale composites on the surface of reaction electrode surfaces remain significant challenges to the date. Additionally, opportunities to enhance the signal-to-noise ratio, improve transduction and amplify the signal response, are major factors currently hindering the release of sensors into market. Future research works focusing on clearly elucidating the mechanisms of interaction between nanomaterials and biomolecules during device fabrication holds strong potential in clinical diagnosis, food analysis, process control and environmental monitoring soon. However, the applicability of biosensors is limited by the high cost of macromolecule isolation, limited detection potential and the short life span of the identifying molecules.

Cell biosensors

Laboratory- based molecular and biochemical studies involves high cost, longer processing times and skilled human labour to achieve accurate analysis. Whole-cell biosensors could represent an alternative and potential technology. When cells naturally or deliberately encounter external stimuli, such as pollutants and radiation, they may respond in a stimulus specific manner. Such naturally occurring or genetically triggered cell responses can be documented and compared with standard metabolic profiles of cultured cells. For instance, in environmental monitoring, the levels of air pollutants can be reflected by detecting changes in cell proliferation, gene expression and metabolic activity. Moreover, the growth kinetics of cells can serve as an indicator of environmental stress and potential threats to human health (4). Cell-based biosensors are currently employed in detecting air pollution, water quality, biochemical toxin and radiation leakage. In recent past, several whole-cell biosensors have been developed to monitor gas toxicity and support various environmental monitoring applications, such as air quality control, water pollution assessment and radiation leakage detection. The cell bio sensors can monitor remote or imminent dangerous locations in real-time.

Unmanned Aerial Vehicles (UAVs) -Drones

UAVs, also called drones, are variously sized aircrafts that can be either remotely controlled by mobile applications or software- based pre-designed operations for autonomous flights. Autonomous flight of drones is controlled by sensors, global positioning systems (GPS) and embedded systems. The drones possess tremendous potential for spatial data collection and remote manoeuvres. Though referred to as UAVs, their operation requires ground personnel to preplan and compile the data collected. UAVs are often equipped with high precision cameras or sensors for image capture and d structural analysis, along with ground-control stations consisting of laptops, computers or mobiles. In recent years, expanding research initiatives have paved the path for UAV applications across various fields. Apart from military uses, drones support human relief operations, rescue activities and agriculture (Fig. 1).

Classification of Drones

UAVs can be classified based on altitude range, endurance and payload capacity. Alternatively, drones can also be categorized based on the type of aerial platform used. There are four major types of drones based on the aerial platform design.

Fixed Wing Drones

Fixed Wing drones are designed with a fixed wing like conventional aeroplanes and can travel long distances within a stipulated time. However, they cannot hover in open air withstanding gravity like multi-rotor drones. Majorly operated by gas engines, they are widely used for aerial mapping. Although capable of flying for extended durations, they require a proper runway or catapult launcher for take-off operations (5). The drone should be equipped with a parachute for safe landing. With slightly higher costs starting from 2000-20000 USD, the operations of fixed wing drones can be carried out in accordance with domestic regulations and licensing requirements.

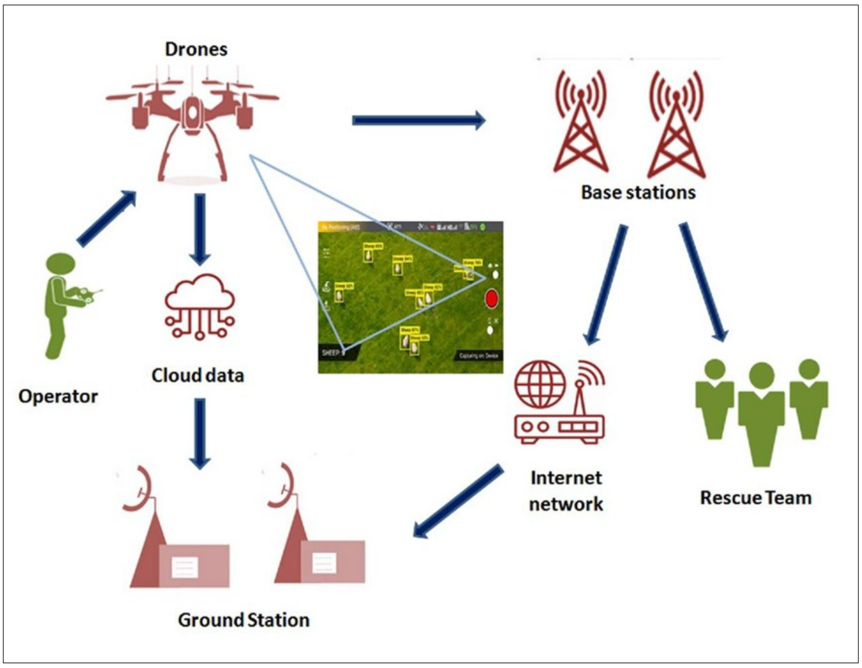

Fig. 1. UAV architecture platform.

Drones in Agriculture

With increasing food demands due to population growth, UAVs offer promising solutions to several limitations in agricultural production. For instance, the UAVs near infrared light can assist in soil health monitoring. Through the application of multispectral photographs, they can also serve as real-time pest and disease surveillance tools. The damages caused by natural calamities can be better documented and serve as authenticated document for crop insurance agencies.

It was estimated that the drone usage in the agricultural market costs about $44.32 billion by 2025. The drones such as DJI Agras MG1 precisely measure the dispersion and rate of application liquid fertilizer, pesticides and fungicides. The high-resolution camera attached with drones' records spectral photographs, thereby enabling the preparation of normalised difference vegetation index (NDVI). The green cover such as grasses, forests, trees and plants either affected by pests and diseases or biotic stress can be identified by difference in RBG colour spectrum maps. The crop water stress index and chlorophyll content index are useful in digital monitoring of crop health. The Near infrared (NIR) light signals received from healthy plant and plant affected by stress can assist in plant management practices. The drones in operation by FAO in the Republic of the Philippines are capable of photogrammetric ground resolution up to 3 cm. The disaster risk reduction and management (DRRM) and Climate Change Adaptation (CCA) can be mainstreamed by the drones (6) The pre-landslide and soil erosion alerts are disseminated by the Ministry of Agriculture, Livestock and Irrigation, Republic union of Myanmar as a joint initiative with FAO. The alerts helped in initiating community-based action in the Rakhine and Chin provinces.

A pilot study in Shandong Province, China, showed that UAV use in agriculture provides real-time, highly accurate farm data for farmers. Through the collection and analysis of data at the control centres, farmers can take timely decisions regarding irrigation, fertigation and plant protection measures. It was also documented that production volume increased by 1.5-2 times, whereas cost of human labour and inputs cost considerably reduced. Through timely application of fertilizers, fertilizer use efficiency increased up to 40 % annually. With 500 acres of pepper and vegetable cultivation, farmers were able to monitor the crop areas for biotic and abiotic stress, as well crop growth stages. However, UAV cost and performance remain the key challenges for large-scale adoption of the technology, particularly ins developing countries.

In the past several decades, standoff mid infrared detection systems and light detection and Ranging (Lidar) techniques have been used for detection and advocacy of anomalies such as forest fires, chemical explosions, air quality surveillance, radiation leakage detection and pollution level detection in urban areas. At the same time, isolating elements from a group of molecules and detecting micro substances have been cumbersome, time-consuming and cost-intensive procedures. The change in environmental quality by chemical agents (CAs), volatile organic chemicals (VOCs) or toxic industrial chemicals (TICs) could be well detected with relatively low cost and high accuracy using flying platform architecture such as UAVs.

Mobility of cell biosensors

System design of cell biosensor Mobility

The whole-cell biosensor system can be planned as a portable model using UAV. The system includes a micro fluidic microbial inoculation channel and a temperature regulation mechanism housed in a lightweight metal box. The microbial inoculation channel can be fabricated from polydimethylsiloxane (PDMS) substance using soft lithography. PDMS is considered ideal due to its chemical inertness, transparency and gas permeability, which support whole cell biosensing applications. The microchannel facilitates effective gas exchange for rapid microbial growth. Owing to their large surface-to-volume ratio, microchannels provide effective gas exchange for rapid bacterial growth without the need for bulky support equipment (7). For instance, in gas pollutant detection applications, molecular dynamic simulation is performed to study the diffusivity of several major pollutant gases in PDMS. Model microbes such as *Escherichia coli* can be incorporated into the whole cell biosensor system. Due to its short doubling time, *E. coli* enables rapid empirical data collection. Microbial growth can be measured and compared using standard bacterial culture techniques. Once optimal growth conditions are maintained, the system can be integrated onto UAVs to facilitate mobile operation. The inoculation temperature can be maintained using automatic feedback control system. The possibility of a microfluidic whole-cell biosensing system integrated onto a UAV opens novel opportunities for detection in remote and inaccessible areas. The drones attached with gas sensors can map the volatile organic chemicals, making environmental monitoring feasible at moderate cost and maximum accuracy (Gas-drone:Portable gas sensing system).

The immobilization of pyruvate dehydrogenase enzyme on Meldolas Blue electrodes, along with a reference/counter electrode combined with Ag/AgCl was carried out (8). Both electrodes were screen-printed on a PVC substrate to develop a disposable carbon-based prototype electrochemical biosensor (C2030519D5, GEM Ltd., Gwent, UK), developed to determine pungency in onions (*Allium cepa* L.). The developed biosensor demonstrated the ability to distinguish between freshly extracted juices from mild and pungent onion bulbs, with pyruvate concentrations ranging between ~4 and 8 mM. An amperometric inhibitor- based biosensor for benzoic acid detection was developed by immobilizing mushroom tissue (*Agaricus bisporus*) homogenate on a Clark-type oxygen electrode in late 90's. The performance of biosensor was uniquely influenced by the homogeneous quantity of mushroom tissue, the quantity of gelatin and the percentage of the cross-linking agent glutaraldehyde. Many phosphate biosensors based on enzymes have recently been developed using fluorescence transduction mechanism, involving the production of fluorescent NPs, enabling precise and rapid phosphate detection. Notably, field or storage surveillance and detection is increasingly being done with drones.

Biosensors have been developed to detect marker volatiles released by *Phytophtora infestans* in infested potato tubers, thereby offering a feasible solution for screening disease- free seed potatoes (9). A biosensor system utilizing the intact antennae of the Colorado potato beetle (*Leptinotarsa* sp.) was capable of detecting a single diseased potato tuber in a pile of up to 100 kg, thus serving as an effective early warning system. These biosensors represent a cutting-edge frontier in food quality and safety management, at the forefront of the agri-food sector.

Globally, significant health consciousness is on the rise, driving increasing emphasis on food safety and food quality. However, current food analysis techniques often require highly skilled manpower and larger time for analyzing the samples. Challenges in the application of microfluidics to food sustainability testing includes complex food matrix preparation and intricate fabrication stages. These issues can be tackled by leveraging physical properties tailored to specific testing targets, developing diverse microfluidic platforms for real food analysis and integrating biomolecules such as food proteins and DNA into microfluidic systems (10).

Earlier studies demonstrated rapid cell growth within micro channels using PID temperature control terminals (11). The ability to culture cells under varied environmental conditions significantly enhances the versatility and applicability of whole-cell biosensors. In future, other cell types, such as slow-growing bacteria, fungi and mammalian cells, could also have the potential for bio sensors research. The gene expression, metabolic activities and genetic modifications could be incorporated to enhance the functions and accuracy of the system.

Cell biosensor mobility using UAVs application in Environmental studies

In recent past, UAVs employed for defense purposes, have been increasingly utilized for environment monitoring. With the advancement in the field of aerial robotics microprocessors and nano sensors, UAV have emerged as a potential tool for checking the volatile chemicals, air quality and pharma studies. The navigation of UAVs carrying payloads can be guided at ease by built-in gyroscopes and compasses. Moreover, automatically guided UAV is currently in operation through unique software and mobile applications. Detection, identification, assessment and sample collection tasks can be accomplished using Photo Ionization Detection (PID) and Ion Mobility Spectrometry techniques (IMS). The earlier studies using electrochemical sensors and sampling systems integrated onto UAV have demonstrated their potential in confirmation of lab test results. Technical specifications, such as weight of the sampling systems, cost incurred, energy consumption and operational complexities, play a critical role in the selection of appropriate UAV types for sample collection. Additionally, the design of cartridge system is decided by factors such as, the nature of samples (aerosol or gases) and user preferences (single use or multiple use) decides. Air sampling pumps used for collecting gas and air samples typically operate at 10 mL- 500 mL flow per minute (SKC Inc). Various sampling media and collection apparatus, such as metal cartridges enables sample collection at any warranted situation. However, UAVs do not function autonomously by default, but requires pre-set alarms from a Lidar sensor network to alert front-line team to initiate UAV operations. Blue tooth operated mobile-based operations as well as micro controller models can efficiently collect samples and generate real time data. Though drones can be efficiently utilized for the detection of suspicious substance or agents in the test environment, trained manpower is needed to convert the detections data into a matrix, thereby determining the quantum of foreign substance as well positioning status.

Cell Biosensor applications in veterinary applications

The livestock sector is a critical component for sustainable agriculture, especially in developing countries under the current global scenario. The existing problems such as epidemic diseases that cause unforeseen animal mortality, can significantly influence a country's economy. Conventional methods are often time-consuming, require large-scale equipment and demand substantial man power. This has resulted in the advent of biosensor technology, which ushers a new and promising approach for the faster diagnosis of animal diseases at the sub-clinical stages.

Reliable advances in sensor technology hold tremendous promise for enhancing animal productivity in the developing world, paving the path for the next level of advancement. Agriculture and animal husbandry involves animals and their products including meat, fiber, milk and eggs, that make a major contribution to a country's food bowl. Early reports have indicated that diverse environmental polluting gases such as ammonia (NH_3), methane (CH_4), nitrous oxide (N_2O), hydrogen sulfide (H_2S) and carbon dioxide (CO_2) are emitted from poultry farms and dairies because of different metabolic activities. To address this issue, various biosensors have been developed for the specific detection and measurement of these released gases within animal shelters. Mastitis, a major mammary inflammatory condition, is one of the leading causes of annual economic loss. It can be caused by a multitude of pathogens with devastating consequences, such as infecting the entire herd. (12). Moreover, the routine use of antibiotics to treat or prevent the disease has led to the emergence of antibiotic resistance. Thus, the use of early diagnostic methods has been well received not only by the farm owners but also by individual farmers, to safeguard their economic status. Researchers have developed biosensors that can detect mastitis and ketosis at early stages, thereby enabling timely treatment and preventing disease progression (13, 14). In addition, biosensors are being used for rapid and sensitive detection of pathogens and for screening of antibiotic residues in animal-derived foods (15). Applications such as tumor-specific drug delivery system, implantable biosensors for animal tracking, detection of parasitic infections (16), genotyping and bio-sensing of chemosensory proteins in insects, disease surveillance and monitoring, poultry feed analysis (17) and waste monitoring can also be detected (18). Furthermore, customized bioelectronic noses have been developed for odor sensing (19) in farms, feed and meat industry. Biosensors have also been integrated into virus-incorporated biomimetic nano composites for tissue regeneration, allergen detection and control.

With all these recent advances in bioelectronic nanotechnology that mimic manual monitoring system, including biological recognition elements, in the fields of diagnosis, manufacturing, production and sensor-based detection the lab-on-chip device has emerged as a potential real-world alternative to standard practices.

Cell biosensors enabled UAVs in food technology diagnostics

A complex workflow of processes in the food processing industry emphasizes quality and safety while maintaining efficient processing and product delivery. Hence, automated methods embedded with sensors for real-time, selective standardization and ensuring consistency in quality of food products is the need of the hour and appears highly promising. To achieve the ambitious enactment of these technologies, fields such as electronics, electromechanics, physical chemistry, material science, nanotechnology and microfluidic systems are rapidly advancing toward the development of customized sensors that are being increasingly prevalent in the market. *In situ* detection of crop toxins and pathogens are now being addressed by UAVs enabled with agricultural biosensors during the process control stages. Recent reports have shown the successful implementation of various sensors such as temperature, pH, gas and optical sensors, in the food industries for detection of pathogens and faecal contaminants in food and vegetables; as well as for real-time analyte measurements such as ammonia and other toxins. The use of light scattering sensors in the detection of microorganisms has been documented in vegetable and meat samples. Similarly, an optical (fluorescence-based) portable array biosensor developed by Naval Research Laboratory was used to detect the presence of *Salmonella typhimurium* within 45 min in milk and apple juice (20). The demand for increased efficiency and quality has recently led to a surge in genetically modified (GM) foods. Among several reported studies, a label-free colorimetric biosensor has recently been developed to identify GM foods using a fast and sensitive technique.

Cell biosensor mobility using UAVs application in Agric-Horti domains

Feeding over 9 billion people by 2050 demands smarter agricultural technologies. At present, the focus is placed on the impact of nanotechnologies and biosensors such as, quantum dot nanosensor, dNA nanobiosensor and AChE biosensor, etc., on the creation of fast, effective, responsive, affordable and user-friendly technologies that are well-suited to upscaling agriculture production. Biosensors now integrate biology, engineering and computer science to offer practical solutions across agriculture. Based on their operations, various models of UAVs are currently in use. For instance, from pest surveillance to weed management and from irrigation management to artificial pollination, various UAV models have been adopted by farmers. Some of the commonly used models for agricultural operations are listed in Table 1, 2 (21).

Optimum crop yields can be achieved with limited losses from various plant stresses such as drought, lack of nutrients and diseases. Biosensors such as ECH2O soil moisture sensor and TPS-2 portable photosynthesis system are now being developed to detect plant physiological indicators daily. Different indicative signals such as, increases in sucrose content and, changes in nutrient concentration (22) can be converted into the sensory signal using biosensing signal processing technology. Plant stresses have been monitored through imaging or spectrometry of plant leaves using high resolution cameras mounted on UAVs, further enhanced by fluorescence imaging or fluorescence spectrometry. In plant stress detection, the integration of data from multiple sensors has proven successful. UAV equipped with suitable sensor attachments for agriculture use is presented in Table 2.

Detection and identification of infectious disease in crops

The microbial pathogens including certain bacteria genera, such as *Erwinia*, *Pectobacterium*, *Pantoea*, *Agrobacterium* and *Pseudomonas*, etc. as well as phytopathogenic fungi attack plant species under conducive environment, resulting in epidemic plant diseases. Fungal infections and aflatoxin production can occur at various stages of plant growth, as well as during harvesting, drying, processing and storage. The ingestion or inhalation of aflatoxins can cause serious respiratory and gastrointestinal disorders as well as ailments like haemorrhage, anorexia, fever, hepatic encephalopathy and

Table 1. UAV models in agricultural operations

Application in agriculture	UAV models	Crops	Sensor
Sky farming and Crop monitoring	Fixed wing, Hexacopter and Quadcopter	Wheat, Soya, Oats, coffee	Digital, Hyper spectral and Multispectral camera
Precision Agriculture	Fixed wings and Rotary wings	All types of crops mainly Grapes, potato, Rice and Pomegranate	RGB, Hyper-spectral, Multispectral and Thermal camera
Irrigation management	Fixed wing and Quadcopter	Grapes, Orange, Barley and Almond	Digital, Micro Hyper-spectral, Multi spectral
Aerial Mustering	Fixed wing, Hexacopter	Stock mustering	Digital, multi spectral and Hyper spectral
Artificial pollination	Helicopter, Hexacopter and Quadcopter	Rice, Apple, Almonds, Cherries and Pears	Windspped sensor, HD digital camera

Table 2. Various sensors in agricultural operations

Sensors	Available Agrl. Sensors	Power consumption	Connection time	Data rate	Potential application
Location based sensors	GPS receiver	Battery operated	NA	NA	Precision Agriculture
Optical sensors	Camera	Battery operated	1 sec	5 Mbps	Precision Agriculture, Soil properties measurement
Thermal sensors	Thermal camera	Battery operated	1 min	1 Mbps	Irrigation scheduling, disease detection, mapping soil texture, Crop maturity monitoring and Yield mapping
Thermal and Humidity sensors	Wireless temperature and Humidity sensors	Battery operated	NA	NA	Agriculture fields and green house temperature, humidity monitoring. Fertilizer and water quality checking

liver damage. The use of nanosensors has been seen as the most beneficial approach to the detection of pathogens in the healthcare and food industries. Their quick and high sensitivity further extends their use in agriculture for disease assessment. The combination of multispectral and hyperspectral imaging has been employed to detect yellow rust in wheat. A special type of biosensor was also earlier developed to identify the pathogenic *Phakopsora pachyrhizi* fungus which is known to cause soybean rust.

Recently, experimental studies on both crops and meat, have utilized biosensing techniques such as immunoassay, electrochemical impedance spectroscopy (EIS), cyclic voltammetry (CV), time-resolved spectroscopy, voltammetry of square waves, etc. Phytohormone imbalance problems and related effects can also be resolved with the help of biosensors. A label-free electrochemical impedance immunosensor was developed by adsorbing anti-abscisic acid (ABA) antibody onto a porous nanogold film for the detection of ABA. The various signaling molecules including jasmonic acid in plants are likely to have growth-regulating functions like other plant hormones. To examine jasmonate signaling in plants, a fluorescence-based biosensor was developed that provides detailed data on hormone distribution under plant abiotic and biotic stress conditions (23). For the quantification of indole-3-acetic acid, an amperometric biosensor was developed as a chemical indicator of water stress in maize plants. Biosensors have also been used to calculate the intrinsic content of key horticultural crop characteristics such as ascorbic acid, total phenolic compounds and L-arginine. A highly selective micro-biosensor was built for the determination of low cytokinin concentrations (nanomolar) in tomato xylem sap exudates to boost the selectivity of a biosensor (24). The nanomolar-sensitive cytokinin dehydrogenase-based biosensor has a rapid response time of <10 sec, with excellent pH stability and durability.

To enhance electrochemical sensing performance, biosensors based on carbon nanotubes (CNTs), quantum dots (QDs), graphene, gold (Au), silver (Ag), silica, nanocomposites and modified nanostructures with large surface to volume ratios have been synthesized. Plant disease and foodborne disease diagnostics are the major areas for improvement that can be assisted by nanotechnology. It is proposed that ultra-small particles (nano particles (NPs)) might better associate with microorganisms such as bacteria and viruses by mechanisms like membrane interaction, ROS generation, etc., thereby provide a possible solution to pathogenic problems in agriculture.

Detection of pesticide residues in crop and soil samples

Pesticide analysis in crop and soil samples involves labor-intensive extraction and analytical procedure, with significant time requirements and potential for error. A multi-analyte detection method for organophosphates and carbamates was also reported (25). The assay duration was 40 min and the limit of detection for paraoxon and carbofuran in drinking water in separate analyses was of 0.5 mg/mL. Recently, nanocapsules have been developed for the efficient delivery of a variety of agricultural chemicals, such as herbicides, to improve their basic efficiency and effectiveness through slow and regulated release to the environment enabled by targeted activity. Thus drone-based remote sensing and real-time detection systems could be effectively utilized for field-level monitoring of pesticide residues

Future Applications of Cell-Based Biosensors

The diagnostics market is expanding swiftly and encompasses a wide range of disciplines. Developing biosensor-based products could have relative advantages of speed, point-of-care, simplicity, sensitivity, real-time analysis, portability and low-cost technologies. (26) The futuristic implications of biosensors in societal development and scientific frontiers are as follows

i) A wearable cap that can deliver data on body stability (eg., sudden unconsiousness), dehydration level, while monitoring the blood flow in elderly patients who are at risk of stroke/cerebral ischemia.

ii) Spectacles for determining ocular stress in diabetic patients, particularly those suffering from glaucoma, diabetic retinopathy, cataract and eye infections.

iii) A wearable ear device for the identification of ENT infections in patients suffering from vertigo and fatigue.

iv) A wearable necklace for detecting environmental smoke/ contaminants in the workplace, monitoring UV exposure while in sun and detecting heart rate and blood pressure.

v) A wearable abdomen strap for monitoring urine flow in bed -ridden patients and enabling controlled drug for renal stone detection, etc.,

vi) A pair of shoes that can monitor walking patterns in elderly individuals/ patients with foot diseases such as plantar fasciitis, arthritis, etc. to enable early treatment.

vii) A sanitary napkin with markers for early identification of urinary tract infections/ early detection of reproductive disorders in teens.

viii) A wearable skin patch for sweat sensors for metabolite analysis, anti-microbial susceptibility testing to help prevent the development of anti-microbial resistance development and wound healing.

ix) A wearable device for swimmers/runners to monitor health during sports and physical activities and to function as a nutrient monitor.

x) A therapeutic smartphone to monitor psychological well-being to prevent suicidal thoughts is the need of the hour.

xi) Biosensors that can determine cytokine levels and biochemical/ molecular interactions for enhanced selectivity towards a biomarker of interest.

xii) Wearable Sensors including nanomaterials and transducers to sense levels of hormones, drugs, or toxins using biophotonics or other physical principles in regard to aging research.

xiii) A pocket food sensor for gluten detection for celiac patients and other individuals with food allergies.

xiv) Sensors to monitor eutrophication by detecting nitrite and nitrate levels, aimed at enhancing marine resource management.

Conclusion

With the great potential to revolutionize scientific advancement, biosensor systems play a major role with wide applications. As one of the most powerful technologies, these biosensors are emerging as key tools for decision-making support systems that smartly and quickly forecast calamities to prevent losses while ensuring sustainable productivity. Thus, the use of multifaceted biosensors provides opportunities to develop a new generation of biosensor technologies, opening new horizons in multidisciplinary research and real-world monitoring of biological and environmental systems.

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Authors' contributions

In the preparation of this manuscript, NS conceived the study and carried out the collection of review contents, RS carried out the preliminary drafting, BV carried out the interpretation. US participated in the alignment and KCS carried out the coordination. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

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References

1. Siva Balan KC. Biosensors for sustainable food– new opportunities and technical challenges. Compr Anal Chem 2016;74:363-75. https://doi.org/10.1016/bs.coac.2016.04.017
2. Yao S, Ren P, Song R, Liu Y, Huang Q, Dong J, et al. Nanomaterial-enabled flexible and stretchable sensing systems: processing, integration and applications. Adv Mater 2020;32(15):e1902343. https://doi.org/10.1002/adma.201902343
3. Pan M, Gu Y, Yun Y, Li M, Jin X, Wang S. Nanomaterials for electrochemical immunosensing. Sensors (Basel) 2017;17(5):1041. https://doi.org/10.3390/s17051041
4. Lu Y, Macias D, Dean ZS, Kreger NR, Wong PK. A UAV-mounted whole cell biosensor system for environmental monitoring applications. IEEE Trans Nanobiosci 2015;14(8):811-17. https://doi.org/10.1109/TNB.2015.2478481
5. Panagiotou P, Yakinthos K. Aerodynamic efficiency and performance enhancement of fixed wing UAVs. Aerosp Sci Technol 2020;99:55-75. https://doi.org/10.1016/j.ast.2019.105575
6. Siva Balan KC, Nithila S. Farmers' capacity strengthening and climate advisory services for combating climate change in India. J Pharmacogn Phytochem 2018;7(4S):179-82. https://doi.org/10.3390/plants8020034
7. Chen CH, Lu Y, Sin MLY, Mach KE, Zhang DD, Gau V, et al. Antimicrobial susceptibility testing using high surface-to-volume ratio microchannels. Anal Chem 2010;82(3):1012-19. https://doi.org/10.1021/ac9023997
8. Scognamiglio V, Arduini F, Palleschi G, Rea G. Biosensing technology for sustainable food safety. TrAC Trends Anal Chem 2014;62:1-10. https://doi.org/10.1016/j.trac.2014.06.008
9. Schutz S, Weissbecker B, Koch UT, Hummel HE. Detection of volatiles released by diseased potato tubers using a biosensor on the basis of intact insect antennae. Biosens Bioelectron 2000;14 (2):221-28. https://doi.org/10.1016/S0956-5663(99)00130-1
10. Adami A, Mortari A, Morganti E, Lorenzelli L. Microfluidic sample preparation methods for the analysis of milk contaminants. J Sensors 2016;2016:2385267. https://doi.org/10.1155/2016/2385267
11. Arduini F, Cinti S, Scognamiglio V, Moscone D. Nanomaterials in electrochemical biosensors for pesticide detection: advances and challenges in food analysis. Microchim Acta 2016;183:2063-83. https://doi.org/10.1007/s00604-016-1771-0
12. Martins SAM, Martins VC, Cardoso FA, Germano J, Rodrigues M, Duarte C, et al. Biosensors for on-farm diagnosis of mastitis. Front Bioeng Biotechnol 2019;7:186. https://doi.org/10.3389/fbioe.2019.00186
13. Vidic J, Manzano M, Chang CM, Jaffrezic-Renault N. Advanced biosensors for detection of pathogens related to livestock and poultry. Vet Res 2017;48(1):11. https://doi.org/10.1186/s13567-017-0418-5
14. Thiruvengadam M, Venkidasamy B, Selvaraj D, Samynathan R, Subramanian U. Sensitive screen-printed electrodes with the colorimetric zone for simultaneous determination of mastitis and ketosis in bovine milk samples. J Photochem Photobiol B 2020;203:111746. https://doi.org/10.1016/j.jphotobiol.2019.111746
15. Chen T, Cheng G, Ahmed S, Wang Y, Wang X, Hao H, et al. New methodologies in screening of antibiotic residues in animal-derived foods: Biosensors. Talanta 2017;175:435-42. https://doi.org/10.1016/j.talanta.2017.07.044
16. Hemben A, Ashley J, Tothill IE. An immunosensor for parasite lactate dehydrogenase detection as a malaria biomarker - Comparison with commercial test kit. Talanta 2018;187:321-29. https://doi.org/10.1016/j.talanta.2018.04.086
17. Wang Z, Zhang J, Liu L, Wu X, Kuang H, Xu C, et al. A colorimetric paper-based sensor for toltrazuril and its metabolites in feed, chicken and egg samples. Food Chem 2019;276:707-13. https://doi.org/10.1016/j.foodchem.2018.10.047
18. Guerra E, Bolea Y, Gamiz J, Grau A. Design and implementation of a virtual sensor network for smart waste water monitoring. Sensors (Basel) 2020;20(2):358. https://doi.org/10.3390/s20020358
19. Dung TT, Oh Y, Choi SJ, Kim ID, Oh MK, Kim M. Applications and advances in bioelectronic noses for odour sensing. Sensors (Basel) 2018;18(1):103. https://doi.org/10.3390/s18010103
20. Shriver-Lake LC, Erickson JS, Sapsford KE, Ngundi MM, Shaffer KM, Kulagina NV, et al. System for environmental monitoring applications. IEEE Trans Nanobiosci 2015;14:811-17. https://doi.org/10.1109/TNB.2015.2478481
21. Maddikunta PKR, Hakak S, Alazab M, Bhattacharya S. Unmanned aerial vehicles in smart agriculture: Applications, requirements and challenges. arXiv Prepr 2020;arXiv:2007.12874. https://arxiv.org/abs/2007.12874
22. Raul RG, Irineo TP, Gerardo GGR, Miguel CML. Biosensors used for quantification of nitrates in plants. J Sensors 2016;2016:113. https://doi.org/10.1155/2016/1630695
23. Larrieu A, Champion A, Legrand J, Lavenus J, Mast D, Brunoud G, et al. A fluorescent hormone biosensor reveals the dynamics of jasmonate signalling in plants. Nat Commun 2015;6:1-8. https://doi.org/10.1038/ncomms7043
24. Tian F, Greplova M, Frebort I, Dale N, Napier R. A highly selective biosensor with nanomolar sensitivity based on cytokinin dehydrogenase. PLoS One 2014;9:e000000. https://doi.org/10.1371/journal.pone.0090877

25. Bachmann T, Leca B, Vilatte F, Marty JL, Fournier D, Schmid RD. Improved multianalyte detection of organophosphates and carbamates with disposable multielectrode biosensors using recombinant mutants of *Drosophila* acetylcholinesterase and artificial neural networks. Biosens Bioelectron 2000;15:193-201. https://doi.org/10.1016/S0956-5663(00)00090-6

26. Lino C, Barrias S, Chaves R, Adega F, Martins-Lopes P, Fernandes JR. Biosensors as diagnostic tools in clinical applications. Biochim Biophys Acta Rev Cancer 2022;1877(3):188726. https://doi.org/10.1016/j.bbcan.2022.188726

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