Chapter

Perspectives of Nano-Materials and Nanobiosensors in Food Safety and Agriculture

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Abstract

Nanobiosensor is one type of biosensor made up with usage of nanomaterials i.e., nanoparticles and nanostructures. Because of the nanomaterials' unique properties such as good conductivity, and physicochemical, electrochemical, optical, magnetic and mechanical properties, Nanobiosensors are highly reliable and more sensitive in biosensing approaches over conventional sensors which is having various limitation in detection. Quantum dots, nanotubes, nanowires, magnetic and other nanoparticles enhance sensitivity and lower limit of detection by amplifying signals and providing novel signal transduction mechanisms enable detection of a very low level of food contaminants, pesticides, foodborne pathogens, toxins and plant metabolites. Nanobiosensors are having a lot of scope in sustainable agriculture because of its detecting ability i.e., sensing changes occurred in molecular level. So it can be utilized to find out the variations or modification of plant metabolities, volatiles, gas exchange, hormonal and ion concentration etc. which are the indicators of various harsh environmental stresses (abiotic), biotic and physiological stress. Identification of the stress in the starting stage itself will help us to avoid intensive plant damage and prevent yield losses created by the stress. Nanosensors can be used in smart farming, in which all the environmental factors related to plant growth like temperature, water, pH, humidity, nutritional factor etc. are measured and precaution taken to control the factors which reduce the crop production with the help of IOT platform, thereby enhance the productivity. In this review, discussed about nanobiosensors for detection of food contaminants and various application and its potential in agriculture.

Keywords: biosensor, nano material, nano-biosensor, food contaminants, agriculture and smart farming

1. Introduction

Agriculture and food industry are a main source of income and employment for major section of population. Agriculture sector plays a strategic role in the self-sustaining economic development by providing basic ingredients to mankind and raw material for industrialisation. Global estimates indicate, the people engaged in agriculture are about 2.5 billion [1]. Agriculture is much diversified field, but continuing with technological growth at brisk pace. Many advanced technologies are introduced in agriculture to increase the yield by reducing the direct and indirect factors which affect the crop yield. Major yield reduction factors are insect, pathogens and weeds which can be controlled by human beings through application of insecticide, fungicide and herbicide respectively. In order to control these biotic factors and serious intention to increase yield heavy dosage of chemical pesticides and fertilizers are applied to the growing crops. As reciprocation of this residual pesticides and chemicals are contaminating soil food and water. When the contaminated food got consumed, it produce so many serious ill effects to the consumer [2]. Other than chemicals many bacterial pathogens and the toxin produced by the microorganism also major food contaminants and creating more health complications. One of the fine solution for avoiding contaminated food related health issues is effective detection of the food contaminants whether chemical or biological before consumption will ensure the food safety. So many conventional and advanced methods such as culture plate technique, chromatography, spectroscopy, immunology and molecular biology technique etc. are available for detection of biological and chemical contaminants in food sample, but these all are either time consuming, or more expensive and low sensitivity [3]. Agriculture is the primery food source for both human and livestock. So many biotic and abiotic factors are challenging the agriculture production and productivity. To maintain the food security for the fast growing population need to increase the food production and productivity with enormous level [4, 5]. There is need of some advance technology to increase the production in to maximum with higher quality assurance, risk identification, diagnosis and prevention to achieve goal of regional and global food security. Thus to improve consumer livelihood and optimal utilization of resources, rapid, real-time, portable, and cost effective technologies are desired in agriculture and food industry [6–8]. Recently many technologies are developed and revolutionized the agriculture sector, among that, the most promising one is the nanotechnology [9]. Eventhough its practical application is negligible at present moment, it has a lot of scope in near future to improve agricultural practices over conventional farming at various stages from crop production to post harvest, there by flourishing the agriculture sector by enhancing food production and crop productivity. Normally crop productivity or yield enhancement is possible in two ways 1. By reducing the yield loss caused by various factors at different crop stages such as insect and diseases (Biotic stress), various adverse environmental factors (Abiotic stress) i.e. water stress, high temperature stress, salt stress, cold stress, harmful radiation and nutritional deficiency during the crop production stage and avoiding losses after harvesting of farm product (Post harvest stages) 2. Enhancing the yield by adopting highly improved advance crop production techniques there by reducing the cost of inputs and increasing yield with high cost benefit ratio. Nanotechnology can be applied in both of the strategies to improve the production and productivity in agriculture and food sector [10]. Nanobiosenors i.e. biosensors with nanomaterials, is one of the major application of nanotechnology, are synthesized with the help of various departments like, bioelectronics, material science, miniaturization techniques, electrode design, fabrication technology, nanolithography and microfluidics [11–13]. Biosensor is a self contained integrated tool for sensing and characterization of biological materials. Improvement in basic characteristics of biosensors will lead to widespread application in major challenging areas in food and agriculture [14–16]. In this review, role and applications of nanobiosensors in agriculture and food industry at present are explored and also discussed the potential of nanobiosensor, possible application with brisk development and benefits in future.

2. Biosensor

A **sensor** is a device, module, machine, or subsystem whose purpose is to detect events or changes in its environment like temperature, humidity, water

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flow, intensity of light etc. and send the information to other electronic circuit or electrical instrument that can be measured and/or analyzed. Biosensor is a one type of sensing technology consisting of biological component, such as a cell, enzyme or antibody, connected to a tiny transducer, a device changing one form of signal in to another form so that it can be easily measured by other system. The biosensors enable to sense changes that happen in the cells in cells and molecules even in very low concentration of the tested material. When the substance binds with the biological component, the transducer produces a signal proportional to the quantity of the substance [17–20]. For example if there is a more number of bacteria in a particular food, the biosensor will produce a strong signal indicating that the food is unsafe to eat. With this technology, mass amounts of food can be readily checked for their safety of consumption [21–23].

The biological element of a biosensor contains a biosensitive layer, which can either contain bioreceptors or be made of bioreceptors covalently attached to the transducer. The different types of biosensors are classified based on the bioreceptor and transducer present in the biosensor [24–27]. Based upon biorecepting molecules majorly it is divided in to five categories.

1. Protein based mainly Antibody/antigen based,

2. Enzymes based,

3. DNA based.

4. Based on cellular interactions either whole cells or cell organelles,

5. Employing biomimetic materials (e.g., synthetic bioreceptors).

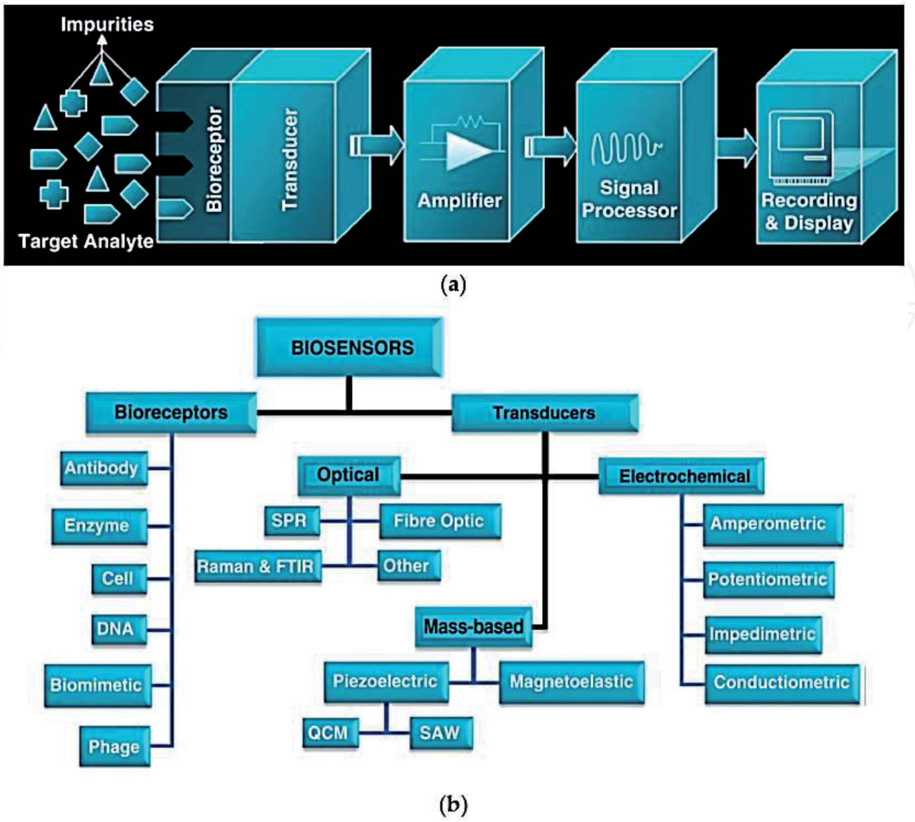

Figure 1.
Various components of a typical Biosensor (a) and its classification (b) [25].

By using of the transducer, mainly it is divided in to three types, those are, 1. Electrochemical, 2. Mass based and 3. Optical Biosensor.

In these major types is divided in to many subtypes based upon the mechanism of signal detection (**Figure 1**).

Biosensors especially nanobiosensors can overcome all the disadvantages of conventional detection methods by offering a rapid, non-destructive and affordable methods for quality control [28, 29].

3. Nanobiosensor

Biosensors are synthesized using nanomaterial is called nanobiosensor. This type of biosensor can able to detect the changes happen in the atomic level with more accuracy. In normal biosensor s receptor and transducer materials are made up of normal micro and macro sized material, but in nanobiosensor either receptor or transducer or both are made up of nano material i.e. at least any one dimension is less than 100 nm [30, 31]. Nanomaterials are very small size, so it is having unique physical, mechanical, optical, electrical and magnetic characters when compared to the conventional material. This is the added advantage of the nanobiosensor and reason for all the superior sensing qualities. Researchers have used various nanomaterials and nanocomposites to enhance the sensitivity, shelf life and get the precision in the biosensing results [32, 33]. Mostly four types of nanomaterials i.e., carbon based, metal based, polymer based and nanocomposites are used for various field application [34]. Perhaps among four, dendrimer is not used that much as frequently as other nanomaterial in the bio sensing field. Carbon nanotubes (CNTs), quantum dots (QDs), gold (Au), silica, silver (Ag), graphene and other nanocomposites are synthesized in such a way having large surface area to volume ratio to improve electrochemical parameters (**Figure 2**). The molecular binding is a subject of the biological surface science, which is strongly related to the research on modification of nanostructures properties by controlling their structure and surface

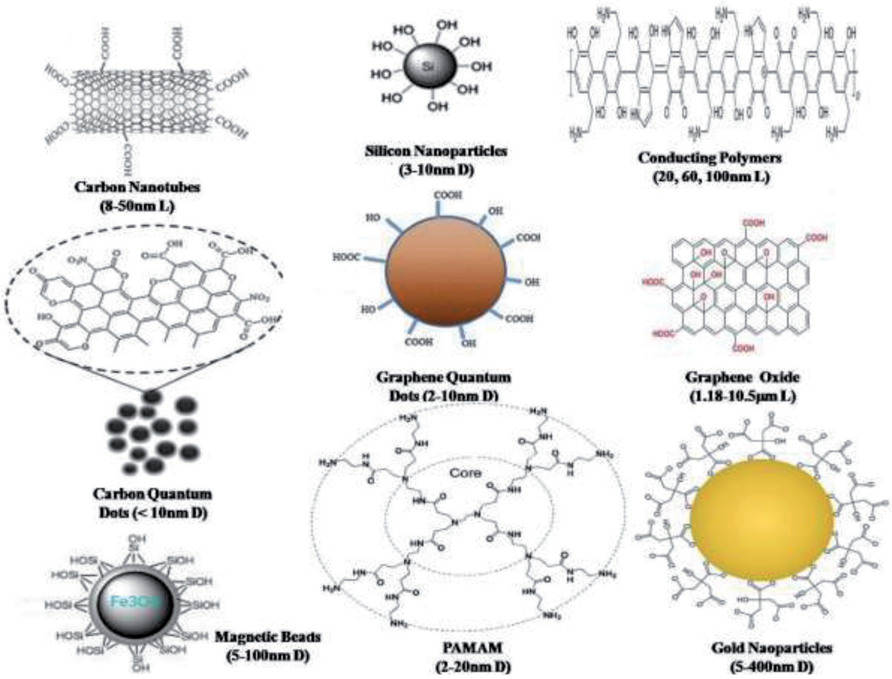

Figure 2.
Commonly used nanomaterials in various kind of sensors fabrication with their sizes. L: length; D: Diameter [35].

at a nanoscale level [36, 37]. Recent technological advancement in nanotechnology enable to synthesize nanomaterials with extraordinary optical and electronic properties for electronics and sensing applications [38]. The efficiency of biosensor can be improved by increase the detection limit and the overall performance through using nanomaterials. Nanomaterials provide friendly platform for the assembly of bio-recognition element, the high surface area, high electronic conductivity that increase the limit of detection [39].

4. Nanobiosensor application in food

Harmful microorganisms such as pathogenic bacteria, viruses, or parasites and its toxin and excessive use of agrochemicals (pesticides, herbicides and food preservative) are the common causes of food contamination. The primary contaminants leading to foodborne illness are pathogenic microorganisms including: *Bacillus cereus, Clostridium botulinum, Escherichia coli (E. coli), Listeria monocytogenes, Salmonella* and *Staphylococus aureus* [40]. Currently, there are limited methods for field detection of toxins and foodborne pathogens, making early identification of a possible contamination is much difficult because of the low efficient conventional methods. The biosensors integration with various nanostructures like thin films, nanorods, nanoparticles and nanofibers, in the analysis methods for detection of food contaminants has improved the detection sensitivity and increased portability. In food microbiology, nanosensors or nanobiosensors are used for the detection of pathogens in processing plants or in food material, quantification of available food constituents, alerting consumers and distributors on the safety status of food [26, 41].

4.1 Nanobiosensors for food pathogen detection

The conventional method for food pathogen detection is colony counting (CFU) on an agar plate which takes 2–3 days for initial results, and up to 1 week for confirming pathogen specificity [42]. These conventional method is not suitable for highly perishable food products. Polymerase chain reaction (PCR) and enzyme-linked immunosorbent assay-based (ELISA) can be used as alternative to traditional CFU methods [43]. But these methods are labour-intensive and costly. So using nanobiosensor, that can be adapted on portable platforms to enable rapid testing of wide range of pathogens with potential for on-site analysis [44]. A dimethylsiloxane microfluidic immunosensor integrated with specific antibody immobilized on an alumina nanoporous membrane was developed for rapid detection of foodborne pathogens *Escherichia coli O157:H7* and *Staphylococcus aureus* with electrochemical impedance spectrum [45]. Due to good electrical conductivity and ample functional groups present on surface area carbon nanotubes have been used to develop biosensors for detection of foodborne pathogenic bacteria (*Staphylococcus aureus*) in fresh meat [46]. Miranda et al. developed a hybrid colorimetric enzymatic nanocomposite biosensor for the detection of *E. coli* in aqueous solutions based on enzyme amplification. The efficiency of the method was demonstrated in both solution and test strip format [47]. β-galactosidase an anionic enzyme is electrostatically attached to the cationic Gold nanoparticles (AuNPs) featuring quaternary amine head groups by this way it inhibit the activity of enzyme. When AuNPs binds with bacteria, the attached β-galactosidase is released restoring its activity and this binding activity and colour formation because of the enzymatic reaction was measured by colorimetric means. Using this method, bacteria can be detected at the concentrations of 1×10^2 bacteria/mL in solution [48]. In an effort to ensure food safety, *Escherichia coli (E. coli)* O157:H7 has been detected using synthesized attractive 3D architecture of silver (Ag) nanoparticles as nanoflowers as the interface material for electrochemical biosensing [49]. Bovine serum albumin (BSA) has been used as stabilizing agent for proper conjugation of Ag nanoflowers. *Salmonella* spp. a food pathogenic organism responsible for causing salmonellosis diseases, [50] millions of people are naffected by this disease annually in all over the World [50–52]. Magnetic nanoparticles and TiO2 nanocrystals are used to detect the *Salmonella* in milk [53]. In this method the pathogen is first captured by antibody-immobilized magnetic NPs. Then antibody-conjugated TiO2 binds the MNP–*Salmonella* complexes and this was monitored by absorbance measurement. This method sensitive enough to detect of 100 CFU/mL for Salmonella in milk sample [53].

4.2 Detection of mycotoxins

Mycotoxin is the toxic metabolites secreted by fungus during its growth and development. Some of the major example for mycotoxin are ochratoxin synthesized by penicillium, aflatoxin secreted by *Aspergillus.* Many agricultural and horticultural food crops are easily affected by different group of pathogenic fungi so invariably food material produced from the affected plants contaminated with mycotoxins. The importance of the mycotoxin is, these create severe health complication even at in small concentrations [54, 55]. Many type of nanomaterial are used to synthesize the nanobiosensor, among all carbon based nanomaterials graphene and its derivatives have great oppurtunity to detect the mycotoxins from various food sample. A nanocomposite of graphene oxide and gold nanocomposites (GO/AuNCs) has high sensitivity detection of aflatoxin B1 (AFB1) in peanut samples [56, 57]. The improvement in sensitivity of the biosensor is due to better quenching ability of nanocomposite. Moreover low detection limit with wide linear range leads to better reliability and wider applicability of such biosensors. Gold nanoparticle (AuNP) based aptasensor is used to detect the aflatoxin B1 with a detection limit of 7 nM [58, 59].

4.3 Detection of pesticides

After green revolution the application and usage of chemical pesticide shoots very high in order to get more yield. In this farmers might have got success in the sense of productivity but at the same time contamination of food material with chemical pesticide is also unavoidable, this issue creates insecurity in the food safety. Organophosphorus (OP) and carbamates (C) are the pesticides used mostly representing ~40% of the world pesticide market [60, 61]. Acetylcholinesterase (AChE) is one of the important enzyme in our body, this catalyses the hydrolysis of neurotransmitter acetylcholine. Primarily the pesticide molecule inhibit this enzyme activity, hence pesticide toxin presence in food ultimately affect the human body dangerously [62, 63]. In order to avoid this the food material should be analysed and detected the amount of pesticide residues exist before its consumption. Commercially many techniques such as chromatographic techniques (GC and HPLC) and coupled chromatographic-spectrometric procedures such as GC–MS and HPLC-MS are available, perhaps these methods are more costlier and not able to do the real time analysis [64]. Mostly pesticide detection is done by measuring AChE activity before and after exposure to the pesticides through colorimetric Ellman assay [65]. AuNPs (3 nm) nanoparticles based biosensors are used to detect the many pesticide molecule like paraoxon, dimethoate, carbaryl, chlorpyrifos, carbofuran, etc. at a concentration of 24 μg/mL [66–69]. The Lum-AgNPs were used in conjunction with a H_2O_2 based CL detection to generate a CL "fingerprinting" related to each specific pesticide. A highly reproducible and stable biosensor based on chitosan-TiO_2 graphene nanocomposite has been developed recently for detection of organophosphate pesticides in cabbage. The porosity of the nanocomposite provides additional stability to the biosensor via efficient enzyme immobilization [70].

4.4 Detection of metal contaminants

Heavy metal ions like mercury, lead, cadmium, arsenic etc., are present in the environment. When food crops are cultivated in such environment, heavy metal residues are accumulated in food. Consumption of this heavy metal contaminated food will create various disorders and health issues such as neurological, reproductive, cardiovascular problems [71]. AuNP-based sensors working based upon colorimetric detection was used to detect the metal ions in water with the detection limits of 30 ppb for Pb^{2+} and 89 ppb for Al^{3+} [72]. AuNPs based sensors also used to detect the other heavy metals like Hg^{2+} [73–77], Cu^{2+} and Ag^{+} [78], Mn^{2+} [79], Cd^{2+} [80, 81], Fe^{3+}, Pb^{2+}, Al^{3+}, Cu^{2+}, and Cr^{3+} [77].

4.5 Nanobiosensors for intelligent food packaging or smart packaging

Normally packaging of food helps to maintain the nutrient content and increasing the shelf life. But smart packaging is have an added option, it indicate the temporal and spatial changes occur in the food constituents that contains with in it. Intelligent tags and stickers are combined with nanobiosensing material inside the packaging and nanobiosensor connected with consumers through electronic devises will indicate the real time sensing data about the food material present whether normal or deteriorated from time to time [82–84]. These work by sensing through a nanobiosensor integrated with polymer film or polymer matrix and radio frequency identification (RFID) components are used by intelligent tags to sensing [85, 86]. Biosensors for food packaging can function in particular physico-chemical conditions in the packaged microenvironment. Zeolite-molybdate tablets are prepared by placing Ammonium molybdate in to the zeolite nanopores used to detect and measure ethylene in avocados packages. In ten day old package, the zeolite-molybdate tablet changes its colur from yellow to blue because of the redction of Mo(VI) to Mo(V) [87–89].

4.6 Nanobiosensors in E-nose technology

Most common factors for food rotting and developing of foul odor in food is pathogenic bacteria. Above certain level of odors can be sensed by the human nose, but sometimes it may not be useful to prevent of food poisoning. Therefore, rapid assessment of odor at earlier stage should be most useful, in this regard nanobiosensors can be used for the detection of these odors with high sensitivity. Nanoparticles help in better absorption of gas on sensor surface due to more surface area than macroscopic particles [90, 91].

Electronic nose (E-nose) is used to identify different types volatile organic compounds present in food to ensure good quality, uniformity and consistency of raw material during mixing, cooking and of final product during packaging and storage processes [92]. Gas sensors composed of nanoparticles e.g. ZnO nanowires are used to detect the gas. More amount of ethylene gas fruits and vegetables deteriorates its quality, Tungsten oxide–tin oxide nanocomposites have been employed for ethylene sensing [93]. SWCNT field-effect transistor functionalized with human olfactory receptor 2AG1 protein has been employed for sensing fruit odorant amyl butyrate in apricot [94, 95]. Olfactory receptors-functionalized carbon nanotubes-based transistor has been documented for the selective detection of hexanal as olfactory indicator of spoiled milk and oxidized food [96].

5. Application of nanobiosensor in agriculture

Nanotechnology is basically dealing with smallest particles which plays important role in fixing problems exist in agriculture that cannot be solved through existing approaches. The development in synthesis of new nanomaterial and nano-devices depict novel applications in agriculture. One of the applications of nanotechnology is formation of superior biosensors that leads to development of miniature structures known as nanobiosensors, that are greater efficient and well organized when compared to traditional biosensors. Nanobiosensors can be used effectively in agriculture for sensing soil pH, moisture, wide variety of pathogens, plant hormones, plant metabolites, pesticide, herbicide, fertilizers, and metal ions. Appropriate and controlled use of nanobiosensor can support sustainable agriculture for improving crop productivity. It can also help in controlled use of agricultural inputs there by control pollution and lowering cost of cultivation [97].

5.1 Nanobiosensor in crop stress management

Crop growth and production undergo for various stress such as biotic, abiotic and nutritional stress. The plant hormones also called as phytohormones play an important role in control and regulation of physiological processes of development and much importantly involved in the stress response and regulation in plants. Abiotic and biotic stress are inducing various unusual chemical metabolites and different plant hormones in the plants, in order to make necessary arrangements to face the adverse condition in the surrounding environment. For addressing problems related to imbalance of phytohormones and related consequences, nanobiosensors have played a pivotal role in term of detection. So that further recovery action of the plant can be taken very quickly, it prevent the considerable amount of plant damage and yield reduction. Nanobiosensors have most significantly contributed to achieve the ever existing goal of precision in agriculture. For abscisic acid detection, a label-free electrochemical impedance immunosensor has been developed using an anti-ABA antibody that is adsorbed on to a porous nanogold film [98]. With the same biosensing technique different matrices have been tried to obtain desired output. The results indicated that the abscisic acid in plants can be detected successfully using an antobody based nanobiosensor. Gibberellic acid (GA) is detected in the hybrid rice grain samples by electrochemical impedance spectroscopy fabricated with successful grown porous nanogold film and consequently modification of the glassy carbon electrode [99]. Simple amperometric biosensor developed by graphite coated with polypyrrole (PPy) for the determination of salicylic acid in samples of plasma and milk [100]. A real time highly selective nanobiosensor developed for determination of cytokinins and auxion concentrations in tomato xylem sap exudates [101, 102]. It is recommended that precautions are better than cure or remedies in case of plant stresses otherwise at the calamity stage it will cause huge crop loss and poor quality of the produce. Presently, it has been observed that the operational stability of the biosensor is limiting its technological implications in agricultural sector. But this early detection of the alarming stress conditions (Biotic and abiotic stress) of plants will be possible in future with complete growth of nanobiosensing technology. In this direction, some nanobiosensors have been developed to detect indicators or signalling compounds of stress conditions of plants. Recently, to analyse the jasmonate signalling in plants, a fluorescence based biosensor has been developed that exclusively provides data about hormone distribution in conditions of plant abiotic and biotic stresses [103]. Water is important not only for photosynthesis, but also for flow of nutrients and many microelements necessary for healthy crop. An optical fluorescence biosensor for plant water stress detection has been reported [104]. Deficiency of macro and micro nutrients will affect the plant growth, physical strength, grain formation and yield. Detection of the deficient nutrient by nanosensor will help to improve the plant growth and yield; also prevent excess unwanted nutrient application. Enzyme based phosphate biosensors with fluorescent nanoparticles using fluorescence transduction mechanism for specific and rapid detection of phosphate and other nutrients such as nitrogen, calcium and zinc [105, 106].

5.2 Nanobiosensors in smart farming

Nanosensors are very minute and it can sense the soil condition, irrigation requirement, pH of the water and soil, nutrient requirement, disease and pest incidence, soil temperature like many important paramaters by scattering all over the field. Based upon the parameter recorded by the nanosensor, need based action will increase the crop yields and reduces the unwanted manpower resourses like fertilizer, pesticide etc. This nanosensor concept fitting well with the precision farming or smart farming goal. Nanosensors, made up of non-biological materials, such as carbon nanotubes, have ability to sense and signal, acting as wireless nanoantennas, because of their small dimensions, can collect information from numerous different points [107]. External devices can then integrate the data to automatically generate incredibly detailed report and respond to potentially devastating changes in their environment. For instance, connected nanosensors for monitoring soil or plant conditions can alert automatically according to conditions detected by sensors and therefore influence more efficient usage of the fertilizers, herbicide, pesticide, insecticide, etc. Nanobiosensors are now developed with all integrated devices such as power source, sensing unit, detector and display unit in a single chip for detecting the plant stress indicators [108, 109]. For that various indicative signals such as increase in sucrose content [110], change in concentration of nutrients [111, 112] and hormones [103] etc. can be used to further transform these in to visual indication through biosensing technology of processing signals [111, 113].

Nanoscale devices are envisioned that would have the capability to detect and treat diseases, nutrient deficiencies or any other maladies in crops long before symptoms were visually exhibited. This is the future of agriculture, an army of nano-sensors will be scattered like dust across the farms and fields, working like the eyes, ears and noses of the farming world. These tiny wireless sensors are capable to communicate the information they sense. These are programmed and designed to respond various parameters like variation in temperature, humidity and nutrients. The distributed intelligence of smart particles can be networked to respond immediately to any change in environment, hence giving an alert in advance to devise ways and means to deal with environmental variations. By smart dust and gas sensors it is possible to evaluate the amount of pollutants in the environment. The most efficacious approach in this sense is real time detection of parameters by the use of autonomous sensors connected to global positioning system (GPS) [114–117].

5.3 Nanobiosensors to maintain seed purity

Seed production is very difficult process particularly in wind pollinated crops since pollen can fly for long distance. Humidity, wind speed, temperature are some of the factor affect the pollen plight Very effective method to ensure the genetic purity is the detecting pollen load that cause contamination. Bionanosensors can be used to identify the specific contaminating pollen and thus reduces contamination. Novel genes are being incorporated into/seeds and sold in the market. Tracking of sold seeds could be done with the help of nanobarcodes [118] that are encodable, machine - readable, durable and sub-micron sized taggants [119, 120].

5.4 Nanobiosensor for disease detection

Frequently recurring diseases are considered as one of the major factors limiting the crop productivity. Early prediction of the occurrence is the only prevention to eradicate diseases at the root. Such devices can diagnose plant health issues before these actually get visible to the farmer. Antibody conjugated nanoparticles are used to detect *Xanthomonas axonopodis* that causes bacterial spot disease [121]. Optical immunosensors based on Gold nanoparticle and antibody conjugated Fluorescent silica nanoparticles (FSNPs) are being used to detect the karnal bunt disease in wheat and bacterial spot diseases (*Xanthomonas axonopodis* pv. *vesicatoria*) in *Solanaceae* plant respectively [121, 122]. Due to the unique optical properties of Quantum dots (QD) [123] they are used for detection of witches' broom disease of lime (WBDL) caused by *Candidatus* Phytoplasma aurantifolia (*Ca.* P. aurantifolia) using fluorescence resonance energy transfer (FRET) mechanism [124].

Many novel sensor fabricated with nanomaterials have been explored in order to obtain high sensitivity and low limits of detection [125–129]. Methyl salicylate is a volatile compound synthesized more by plant during infection stage, so detection of methyl salicylate or other volatile organic compounds specific for particular diseases will be more helpful to identify the diseases before forming symptoms and to take proper control measures in initial stage itself. Gold nanoparticle and semiconductive metal oxide nanoparticles based amperometric biosensors are used to detect diseases causing different types of bacteria, viruses and fungi [130–134].

5.5 Assessment of harvest index by nanobiosensor

As harvesting of proper mature fruits and vegetables ensure good quality and consumer acceptability, sensing maturity of agricultural produce is very important for good post-harvest quality and enhanced shelf life. The overmature fruits/ vegetables will over ripe and have to be discarded, while immature fruits/vegetables will lead to inferior eating quality for consumers. Thus only proper mature fruits/ vegetables should be harvested at proper time. Physio chemical properties of horticultural crops like fruits and vegetables are linked with their maturity. Changes of these characters are linked to the maturity and real time measurement of these characters will guide the harvesting of crops at proper mature stage only. Nanobiosensors are used for measurement of intrinsic quality attributes of horticultural crops such as ascorbic acid [135], total phenolic compounds [136] and L-arginine [137]. As the crop attains maturity, it is harvested and stored for further processing.

5.6 Biosensors for heavy metal deposits in soil and water

Plants need many elements in the trace level for their healthy growth and metabolism. Soil, water and air are the major source of these elements and plants obtained nutrients from these sources. Accumulation of these heavy metals and elements more than the optimum level cause serious problem to the plants there by to the human up on the food consumption. Heavy metals such as nickel, mercury [138], arsenic [139], lead [140], chromium [141], cadmium and copper [142] are commonly found in contaminated soils [143]. The presence of heavy metals increases oxidative stress in plants, which further triggers synthesis of pigments like chlorophyll and βcarotene [141, 144].

In a research study for simultaneous detection of mercury (Hg^{2+}) and silver (Ag^{+}) ions in drinking water, serum and cell lysate, tungsten disulfide-nanosheets (WS2) based biosensing platform has been developed. The study has implications in environmental monitoring and diagnosis [145]. Heavy metals such as Pb, Ni, Cd, Zn, Co, and Al are detected effectively by cantilever nanobiosensors with phosphatase alkaline in water [146].

5.7 Nanosensors in storage

Inexpensive sensors, cloud computing and intelligent software, hold the potential to transform the agri-food sector. Internet of Things (IoT), is an emerging field in which many more instruments are interconnected to the user agricultural field and internet will increase the precision of the agriculture there by maintain the sustainability and cost effectiveness of agricultural production. The joint application of nanotechnology in IoT creates a new things, namely the Internet of Nano Things (IoNT). Nanosensors, because of their small dimensions, can collect information from numerous different points [107]. External devices can then integrate the data to automatically generate incredibly detailed report and respond to potentially devastating changes in their environment. For instance, connected nanosensors for monitoring soil or plant conditions can alert automatically according to conditions detected by sensors and therefore influence more efficient usage of the fertilizers, herbicide, pesticide, insecticide, etc. Involving nanosensors in the design of smart or intelligent packaging, enable the transfer of information regarding product conditions during distribution or storage. The response generated due to changes related to internal or external environmental factor, are recorded through specific sensors [147, 148] and data are stored in the database. So at any time, from any where those data and parameters related to soil and plant health can be accessed via Internet. Rapid response and detections of unusual parameters' values, are enabled to increase the food quality and safety, that directly influence to human health.

6. Conclusion

Latest improvements in nanotechnology and information and communications technology (ICT) exhibit its great potential towards the agri-food sector. Increased fertilizer efficiency, enhancing the plant nutrient absorbtion, Improved quality of the soil, stimulation of plant growth, the use of precise farming, enhancing the food safety, food processing and pakage, distribution and storage, are some of the benefits of nano-based technology in agricultural and food industry. Efficiency and accuracy of the biosensor on detection of agricultural and food safety parameters will be enhanced by the integration of the nanomaterials. The application of biosensor and its efficiency can also be improved further in future by developing of novel nanomaterials that will boost the agriculture and food sector. Therefore, the full potential of nanotechnology in the agri-food sector is yet to be realized. In the coming decades the convergence among nanotechnology, agriculture engineering, and plant science will lead the path towards food security, sustainability, precision agriculture, automation, robotic farming and cost effective technologies. This innovation in technology has important consequences in agriculture.

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References

[1] Food and Agriculture FAO statistical yearbook 2013. Food & agricultural organization, 2013.

[2] Chauhan, N., Narang, J., Jain, U. Amperometric acetylcholinesterase biosensor for pesticides monitoring utilising iron oxide nanoparticles and poly (indole-5-carboxylic acid). Journal of Experimental Nanoscience. 2016; 11 111-122.

[3] Fang, Y., Ramasamy, R.P. Current and prospective methods for plant disease detection. Biosensors, 2015; 5 537-561.

[4] Gruere, G. Narrod, C., Abbott, L. Agriculture, Food, and Water Nanotechnologies for the Poor: Opportunities and Constraints, IFPRI Policy Brief, Vol. 19, 2011.

[5] Joseph, T., Morrison, M. Nanotechnology in agriculture and food, Nanoforum Report, 2006; 2 2-3.

[6] Mustafa, F., Andreescu, S. Chemical and biological sensors for food-quality monitoring and smart packaging, Foods, 2018; 7(10) 168.

[7] Gallocchio, F., Belluco, S., Ricci, A. Nanotechnology and food: brief overview of the current scenario, Procedia Food Sci., 2015; 5 85-88.

[8] Farahi, R.H., Passian, A., Tetard, L., Thundat, T. Critical issues in sensor science to aid food and water safety. ACS Nano 2012; 6 4548-4556.

[9] Sekhon, B.S. Nanotechnology in agri-food production: an overview, Nanotechnol Sci Appl. 2014; 7 31-53.

[10] Dasgupta, N., Ranjan, S., Mundekkad, D., Ramalingam, C., Shanker, R., Kumar, A. Nanotechnology in agro-food: from field to plate. Food Res Int. 2015; 69 381-400.

[11] Bhatia, S. Nanoparticles types, classification, characterization, fabrication methods and drug delivery applications. Natural polymer drug delivery systems Springer. 2016; 33-93.

[12] Ettenauer, J., Zuser, K., Kellner, K., Posnicek, T., Brandl, M. Development of an automated biosensor for rapid detection and quantification of E. coli in water. Procedia Engineering. 2015; 120 376-379.

[13] Sangadevan, S., Periasamy, M. Recent trends in Biosensors and their Application. Revised Advance Material Science. 2014; 62-69

[14] Reddy, M.N.K., Ratna, N.P. Nanobiosensors. Advance in Electronic and Electric Engineering. 2013; 3(3) 321-326.

[15] Cui, D., Guo, Q., Zhang X. Recent Advances in Nanotechnology Applied to Biosensors. Sensors. 2015; 15 30736-30758.

[16] Weiss, P.S. Nanoscience and nanotechnology: present and future. ACS Nano 2010; 4 1771-1772.

[17] You, C., Bhagawati, M., Brecht, A., Piehler, J. "Affinity Capturing for Targeting Proteins into Micro and nanostructures," Analytical and Bioanalytical Chemistry. 2009; 360 (6-7) 1563-1570.

[18] Velasco, M.N. "Optical Biosensors for Probing at the Cellular Level: A Review of Recent Progress and Future Prospects," Seminars in Cell & Developmental Biology. 2009; 20 (1) 27-33.

[19] Fan, X., White, I.M., Shopova, S.I., Zhu, H., Suter, J.D., Sun, Y. "Sensitive Optical Biosensors for Unlabeled Targets: A Review," Analytica Chimica Acta. 2008; 620 (1-2) 8-26.

[20] Khanna, V.K. "New-Generation Nano-Engineered Biosensors, Enabling Nanotechnologies and Nanomaterials," Sensor Review, Vol. 28, No. 1, 2008, pp. 39-45.

[21] A. Shana and K. R. Rogers, "Biosensors," Measurement Science and Technology, 1994; 5 461-472.

[22] Sharma, H., Agarwal, M., Goswami, M., Sharma, A., Roy, S.K. Biosensors: tool for food borne pathogen detection. Vet World. 2013; 6: 968-973.

[23] Bhalla, N., Jolly, P., Formisano, N., Estrela, P. Introductrion to bisensors. Essay Biochem. 2016; 60 1-8.

[24] Su, L., Jia, W., Hou, C., Lei, Y. Microbial biosensors: A review. Biosens Bioelectron. 2011; 26 1788-1799.

[25] Velusamy, V., Arshak, K., Korostynska, O., Oliwa, K., Adley, C. An overview of foodborne pathogen detection: In the perspective of biosensors. Biotechnol Adv. 2010; 28 232-254.

[26] Meshram, B.D., Agrawal, A.K., Adil, S., Ranvir, S., Sande, K.K. Biosensor and its application in food and dairy ındustry: A review. Int J Curr Microbiol App Sci. 2018; 7: 3305-3324.

[27] Singh, R., Mukherjee, M.D., Sumana, G., Gupta, R.K., Sood, S. Biosensors for pathogen detection: A smart approach toward clinical diagnosis. Sens Actuators B. 2014; 197 385-404.

[28] Ozoglu, O., Unal, M.A., Altuntaş, E.G. Biyosensörler: gıda ve sağlık alanında laktat biyosensorleri. Turk J Life Sci, 2017; 2 180-193.

[29] Neethirajan, S., Ragavan, V., Weng, X., Chand, R. Biosensors for sustainable food engineering: challenges and perspectives. Biosensors. 2018; 8 23

[30] Doria, G., Conde, J., Veigas, B., Giestas, L., Almeida, C., Assuncao, M., Rosa, J., Baptista, P.V. Noble Metal nanoparticles for Biosensing Applications. Sensors. 2012; 12 1657-1687.

[31] SRackauskas, S., Barbero, N., Barolo, C., Viscardi, G. ZnO Nanowire Application in Chemoresistive Sensing: A Review. Nanomaterials (Basel). 2017; 7(11) 381.

[32] Anam, M., Yori, O., Romana, S., Muhammad, A., Waheed, S., Sadia, Z. Nanosensors for diagnosis with optical, electric and mechanical transducers RSC Adv. 2019; 9 6793.

[33] Maduraiveeran, G., Jin, W. Nanomaterials based electrochemical sensor and biosensor platforms for *environmental* applications. Trends Environ. Anal. Chem. 2017; 13 10.

[34] Khan, I., Saeed, K., Khan, I. Nanoparticles: Properties, applications and toxicities Arabian Journal of Chemistry. 2019; 12 908-931.

[35] Kumar, H., Kuca, K., Bhatia, S. K., Saini, K., Kaushal, A. , Verma, R., Bhalla, T.C. Kumar, D. Applications of Nanotechnology in Sensor-Based Detection of Foodborne Pathogens. Sensors. 2020; *20*(7), 1966.

[36] Khanna, V.K. in Nanosensors, Physical Chemical and Biological (CRC Press, India) 2011; 1st ed., Chap. 2.

[37] Lim, T.C., Ramakrishna, S. A Conceptual Review of Nanosensors. Z. Naturforsch., 2006; 61, 402.

[38] Shipway, A.N., Katz, E., Willner, I. Nanoparticle arrays on surfaces for electronic, optical, and sensor applications. Chem. Phys. Chem. 2000; 1 18-52.

[39] Saini, R.K., Bagri, L.P., Bajpai, A.K. New Pesticides and Soil Sensors, ed. A.

Grumezescu Elsevier, Amsterdam. 2017; Chap. 14.

[40] Inbaraj, B.S., Chen, B. Nanomaterial-based sensors for detection of foodborne bacterial pathogens and toxins as well as pork adulteration in meat products. J. Food Drug Anal. 2015; 24 15-28.

[41] Thakur, M.S, Ragavan, K.V. Biosensors in food processing. J Food Sci Technol. 2013; 50: 625-641.

[42] Poltronieri, P., Mezzolla, V., Primiceri, E., Maruccio, G. Biosensors for the Detection of Food Pathogens. Foods. 2014; *3* 511-526.

[43] Hossain, S.Z., Ozimok, C., Sicard, C., Aguirre, S.D., Ali, M.M., Li, Y., Brennan, J.D. Multiplexed paper test strip for quantitative bacterial detection. Anal. Bioanal. Chem. 2012; *403* 1567-1576.

[44] Tan, L., Schirmer, K. Cell culture-based biosensing techniques for detecting toxicity in water. Current Opinion in Biotechnology. 2017; 45, 59-68.

[45] Abdalhai, M.H., Maximiano Fernandes, A., Bashari, M., Ji, J., He, Q., Sun, X. Rapid and sensitive detection of foodborne pathogenic bacteria (staphylococcus aureus) using an electrochemical DNA genomic biosensor and its application in fresh beef. Journal of Agricultural and Food Chemistry, 2014; 62 12659-12667.

[46] Huang, H., Liu, M., Wang, X., Zhang, W., Yang, D.-P., Cui, L. Label-free 3D Ag nanoflower-based electrochemical immunosensor for the detection of *Escherichia coli* O157: H7 pathogens. Nanoscale Research Letters, 2016; 11, 507.

[47] Miranda, O.R., Li, X., Garcia-Gonzalez, L., Zhu, Z.J., Yan, B., Bunz, U.H., Rotello, V.M. Colorimetric Bacteria Sensing Using a Supramolecular Enzyme-Nanoparticle Biosensor. J. Am. Chem. Soc. 2011; *133* 9650-9653.

[48] Jodi Woan-Fei, L., Ab Mutalib, N.S., Chan, K.G., Lee, L.H. Rapid Methods for the Detection of Foodborne Bacterial Pathogens: Principles, Applications, Advantages and Limitations. *Front. Microbiol*. 2015; *5*, doi:10.3389/fmicb.2014.00770.

[49] Amiri, M., Bezaatpour, A., Jafari, H., Boukherroub, R., Szunerits, S. Electrochemical Methodologies for the Detection of Pathogens. ACS Sensors, American Chemical Society. 2018; 3 (6) 1069-1086.

[50] Stephen Inbaraj, B., Chen, B.H. Nanomaterial-based sensors for detection of foodborne bacterial pathogens and toxins as well as pork adulteration in meat products. J. Food Drug Anal. 2016; 24(1) 15-28.

[51] Hendriksen, R.S., Vieira, A.R., Karlsmose, S., Lo Fo Wong, D.M., Jensen, A.B., Wegener, H.C., Aarestrup, F.M. Global monitoring of Salmonella serovar distribution from the World Health Organization Global Foodborne Infections Network Country Data Bank: Results of quality assured laboratories from 2001 to 2007. *Foodborne Pathog. Dis.* 2011; *8* 887-900.

[52] Amagliani, G., Brandi, G., Schiavano, G.F. Incidence and role of Salmonella in seafood safety. Food Res. Int. 2012; *45* 780-788.

[53] Joo, J., Yim, C., Kwon, D., Lee, J., Shin, H.H., Cha, H.J., Jeon, S. A facile and sensitive detection of pathogenic bacteria using magnetic nanoparticles and optical nanocrystal probes. Analyst. 2012; *137* 3609-3612.

[54] Cheli, F., Pinotti, L., Campagnoli, A., Fusi, E., Rebucci, R., Baldi, A. Mycotoxin Analysis, Mycotoxin-Producing Fungi Assays and Mycotoxin

Toxicity Bioassays in Food Mycotoxin Monitoring and Surveillance. Ital. J. Food Sci. 2008; *20* 447-462.

[55] Hussein, H.S., Brasel, J.M. Toxicity, metabolism, and impact of mycotoxins on humans and animals. Toxicology. 2001; *167*, 101-134.

[56] Fernandez-Cruz, M.L., Mansilla, M.L., Tadeo, J.L. Mycotoxins in fruits and their processed products: Analysis, occurrence and health implications. J. Adv. Res. 2010; *1* 113-122.

[57] Li, Z., Xue, N., Ma, H., Cheng, Z., Miao, X. An ultrasensitive and switch-on platform for aflatoxin B 1 detection in peanut based on the fluorescence quenching of graphene oxide-gold nanocomposites. Talanta, 2018; 181, 346-351.

[58] Hosseini, M., Khabbaz, H., Dadmehr, M., Ganjali, M.R., Mohamadnejad, J. Aptamer-Based Colorimetric and Chemiluminescence Detection of Aflatoxin B1 in Foods Samples. Acta Chim. Slov. 2015; *62* 721-728.

[59] Luan, Y., Chen, J., Xie, G., Li, C., Ping, H., Ma, Z., Lu, A. Visual and microplate detection of aflatoxin B2 based on NaCl-induced aggregation of aptamer-modified gold nanoparticles. Microchim. Acta. 2015; *182* 995-1001.

[60] Singh, B.K., Walker, A. Microbial degradation of organophosphorus compounds. FEMS Microbiol. Rev. 2006; *30* 428-471.

[61] Kumar, S.V., Fareedullah, M., Sudhakar, Y., Venkateswarlu, B., Kumar, E.A. Current review on organophosphorus poisoning. Arch. Appl. Sci. Res. 2010; *2* 199-215.

[62] Andreescu, S., Marty, J.L. Twenty years research in cholinesterase biosensors: From basic research to practical applications. Biomol. Eng. 2006; *23* 1-15.

[63] Pope, C.N. Organophosphorus pesticides: Do they all have the same mechanism of toxicity? J. Toxicol. Environ. Health B Crit. Rev. 1999; *2* 161-181.

[64] Valdes, M., Valdes Gonzalez, A., García Calzón, J., Diaz-García, M. Analytical nanotechnology for food analysis. Microchim. Acta. 2009; *166* 1-19.

[65] Perez-Lopez, B., Merkoci, A. Nanomaterials based biosensors for food analysis applications. Trends Food Sci. Technol. 2011; *22* 625-639.

[66] Ellman, G.L., Courtney, K.D., Andres, V., Featherstone, R.M. A new and rapid colorimetric determination of acetylcholinesterase activity. Biochem. Pharmacol. 1961; *7* 88-95.

[67] Hossain, S.M.Z., Luckham, R.E., Smith, A.M., Lebert, J.M., Davies, L.M., Pelton, R.H., Filipe, C.D., Brennan, J.D. Development of a Bioactive Paper Sensor for Detection of Neurotoxins Using Piezoelectric Inkjet Printing of Sol-Gel-Derived Bioinks. Anal. Chem. 2009; *81*, 5474-5483.

[68] Hossain, S.M.Z. Luckham, R.E., McFadden, M.J., Brennan, J.D. Reagentless Bidirectional Lateral Flow Bioactive Paper Sensors for Detection of Pesticides in Beverage and Food Samples. Anal. Chem. 2009; *81* 9055-9064.

[69] Luckham, R.E., Brennan, J.D. Bioactive paper dipstick sensors for acetylcholinesterase inhibitors based on sol-gel/enzyme/gold nanoparticle composites. Analyst 2010; *135* 2028-2035.

[70] Cui, H.F., Wu, W.W., Li, M.M., Song, X., Lv, Y., Zhang, T.T. A highly stable acetylcholinesterase biosensor

based on chitosan-TiO2-graphene nanocomposites for detection of organophosphate pesticides. Biosensors and Bioelectronics. 2018; 99, 223-229.

[71] Kim, H.N., Ren, W.X., Kim, J.S., Yoon, J. Fluorescent and colorimetric sensors for detection of lead, cadmium, and mercury ions. Chem. Soc. Rev. 2012; *41* 3210-3244.

[72] Zhao, C., Zhong, G., Kim, D.E., Liu, J., Liu, X. A portable lab-on-a-chip system for gold-nanoparticle-based colorimetric detection of metal ions in water. *Biomicrofluidics.* 2014; *8* 052107.

[73] Du, J., Wang, Z., Fan, J., Peng, X. Gold nanoparticle-based colorimetric detection of mercury ion via coordination chemistry. Sens. Actuat. B Chem. 2015; *212* 481-486.

[74] Chansuvarn, W., Tuntulani, T., Imyim, A. Colorimetric detection of mercury(II) based on gold nanoparticles, fluorescent gold nanoclusters and other gold-based nanomaterials. TrAC Trends Anal. Chem. 2015; *65* 83-96.

[75] Zhou, Y.; Dong, H.; Liu, L.; Li, M.; Xiao, K.; Xu, M. Selective and sensitive colorimetric sensor of mercury (II) based on gold nanoparticles and 4-mercaptophenylboronic acid. Sens. Actuat. B Chem. 2014; *196*; 106-111.

[76] Chen, G.H. Chen, W.Y. Yen, Y.C., Wang, C.W., Chang, H.T., Chen, C.F., Detection of Mercury (II) Ions Using Colorimetric Gold Nanoparticles on Paper-Based Analytical Devices. Anal. Chem. 2014; *86*, 6843-6849.

[77] Sener, G., Uzun, L., Denizli, A. Colorimetric Sensor Array Based on Gold Nanoparticles and Amino Acids for Identification of Toxic Metal Ions in Water. ACS Appl. Mater. Interfaces. 2014; *6* 18395-18400.

[78] Alizadeh, A. Khodaei, M.M. Hamidi, Z. Shamsuddin, M.B. Naked-eye colorimetric detection of Cu2+ and Ag+ ions based on close-packed aggregation of pyridines-functionalized gold nanoparticles. Sens. Actuat. B Chem. 2014; *190* 782-791.

[79] Annadhasan, M., Muthukumarasamyvel, T., Sankar Babu, V.R., Rajendiran, N. Green Synthesized Silver and Gold Nanoparticles for Colorimetric Detection of Hg2+, Pb2+, and Mn2+ in Aqueous Medium. ACS Sustain. Chem. Eng. 2014; *2* 887-896.

[80] Sung, Y.M. Wu, S.P. Colorimetric detection of Cd(II) ions based on di-(1H-pyrrol-2-yl) methanethione functionalized gold nanoparticles. Sens. Actuat. B Chem. 2014; *201* 86-91.

[81] Liana, D.D., Raguse, B., Wieczorek, L., Baxter, G.R., Chuah, K., Gooding, J.J., Chow, E. Sintered gold nanoparticles as an electrode material for paper-based electrochemical sensors. RSC Adv. 2013; *3*, 8683-8691.

[82] Kuswandi, et al., A novel on-package sticker sensor based on methyl red for real-time monitoring of broiler chicken cut freshness, Packag. Technol. Sci., 2014; 27(1), 69-81.

[83] Kuswandi, B., Nurfawaidi. On-package dual sensors label based on pH indicators for real-time monitoring of beef freshness, Food Control, 2017; 82 91-100.

[84] Schaude, C. et al., Developing a sensor layer for the optical detection of amines during food spoilage, Talanta, 2017; 170 481-487.

[85] El-Nour, K. et al., Gold nanoparticles as a direct and rapid sensor for sensitive analytical detection of biogenic amines, Nanoscale Res. Lett., 2017; 12(1), 231.

[86] Putri, V. et al., Application Nano Zeolite-Molybdate for Avocado Ripeness Indicator, in IOP Conference Series:

Earth and Environmental Science, IOP Publishing, 2019.

[87] Lang, C., Hubert, T. A colour ripeness indicator for apples, Food Bioprocess Technol., 2012; 5(8) 3244-3249.

[88] Mills, A. et al., An O-2 smart plastic film for packaging, Analyst, 2012; 137(1) 106-112.

[89] de Chiara, M.L.V. et al., Photocatalytic degradation of ethylene on mesoporous TiO2/SiO2 nanocomposites: Effects on the ripening of mature green tomatoes, Biosyst. Eng., 2015; 132 61-70.

[90] Ranjan, S., Dasgupta, N., Chakraborty, A.R, Samuel, S.M., Ramalingam, C., Shanker, R., Kumar, A. Nanoscience and nanotechnologies in food industries: opportunities and research trends. J Nanopart Res. 2014; 16 2464.

[91] Dasgupta, N., Ranjan, S., Mundekkad, D., Ramalingam, C., Shanker, R., Kumar, A. Nanotechnology in agro-food: from field to plate. Food Res Int. 2015; 69 381-400.

[92] Wilson, A.D., Baietto, M. Applications and advances in electronic-nose technologies. Sensors. 2009; 9 5099-5148.

[93] Pimtong-Ngam, Y., Jiemsirilers, S., Supothina, S. Preparation of tungsten oxide–tin oxide nanocomposites and their ethylene sensing characteristics. Sensor Actuators A-Phys. 2007; 139:7-11

[94] Kim, T.H., Lee, S.H., Lee, J., Song, H.S., Oh, E,H., Park, H.T., Hong, S. Single-carbon-atomic-resolution detection of odorant molecules using a human olfactory receptor-based bioelectronic nose. Adv Mater.2009; 21 91-94.

[95] Jin, H.J., Lee, S.H., Kim, T.H., Park, J., Song, H.S., Park, T.H., Hong, S. Nanovesicle-based bioelectronic nose platform mimicking human olfactory signal transduction. Biosens Bioelectron. 2012; 35:335-341.

[96] Park, J., Lim, J.H., Jin, H.J., Namgung, S., Lee, S.H., Park, T.H., Hong, S. A bioelectronic sensor based on canine olfactory nanovesicle carbon nanotube hybrid structures for the fast assessment of food quality. Analyst. 2012; 137 3249-3254.

[97] Ghaffar, N., Farrukh, M.A., Naz, S. Applications of Nanobiosensors in Agriculture. In: Javad S. (eds) Nanoagronomy. Springer, Cham. 2020; 10 179-196.

[98] Li, Y.-W., Xia, K., Wang, R.-Z., Jiang, J.-H., & Xiao, L.-T. (2008). An impedance immunosensor for the detection of the phytohormone abscisic acid. Analytical and Bioanalytical Chemistry, 391, 2869-2874

[99] Li, J., Xiao, L.T., Zeng, G.M., Huang, G.H., Shen, G.L., and Yu, R.Q. Immuno-sensor for rapid detection of gibberellin acid in the rice grain. Journal of Agricultural and Food Chemistry, 2005; 53, 1348-1353.

[100] Zavar, M., Heydari, S., & Rounaghi, G. Electrochemical determination of salicylic acid at a new biosensor based on polypyrrole-banana tissue composite. Arabian Journal for Science and Engineering. 2013; 38 29-36.

[101] 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 1-7.

[102] Wend, S., Bosco, C.D., Kampf, M.M., Ren, F., Palme, K., Weber, W. A quantitative ratiometric sensor for time-resolved analysis of auxin dynamics. Scientific Reports, 2013; 3, 1-7.

[103] Larrieu, A., Champion, A., Legrand, J., Lavenus, J., Mast, D., Brunoud, G. A fluorescent hormone biosensor reveals the dynamics of jasmonate signalling in plants. Nature Communications. 2015; 6, 1-8.

[104] Chong, J.P.C., Liew, O.W., Li, B.Q., Asundi, A.K. Optical fluorescence biosensor for plant water stress detection. Saratov fall meeting 2006: Optical technologies in biophysics and medicine: Vol. International Society for Optics and Photonics. 2007; 65350-65358.

[105] Kahveci, Z., Martinez-Tome, M.J., Mallavia, R., Mateo, C.R. Fluorescent biosensor for phosphate determination based on immobilized polyfluorene-liposomal nanoparticles coupled with Alkaline Phosphatase. ACS Applied Materials & Interfaces. 2016; 9(1), 136-144

[106] Barney, B.M., Eberhart, L.J., Ohlert, J.M., Knutson, C.M., Plunkett, M.H. Gene deletions resulting in increased nitrogen release by azotobacter vinelandii: Application of a novel nitrogen biosensor. Applied and Environmental Microbiology. 2015; 81, 4316-4328

[107] Garcia-Martinez, J. The Internet of Things Goes Nano, http://www.scientificamerican.com/article/the-internet-of-things-goes-nano/.2016.

[108] Kuswandi, B., Wicaksono, Y., Jayus, A., Abdullah, A., Heng, L.Y., Ahmad, M. Smart packaging: sensors for monitoring of food quality and safety. Sens. Instrum. Food Qual. Saf. 2011; 5 (3-4), 137-146.

[109] Sassolas, A., Prieto-Simon, B., Marty, J.L. Biosensors for pesticide detection: New trends. American Journal of Analytical Chemistry, 2012; 3 210-232.

[110] Soldatkin, O.O., Peshkova, V.M., Saiapina, O.Y., Kucherenko, I.S., Dudchenko, O.Y., Melnyk, V.G., Development of conductometric biosensor array for simultaneous determination of maltose, lactose, sucrose and glucose. Talanta, 2013; 115 200-207.

[111] Chiou, T.J., Lin, S.I. Signaling network in sensing phosphate availability in plants. Annual Review of Plant Biology. 62; 185-206.

[112] Raul, R.G., Irineo, T.P., Gerardo, G.G.R., Miguel, C.M.L. Biosensors used for quantification of nitrates in plants. Journal of Sensors. 2016; 1-12.

[113] Liew, O.W., Chong, P.C.J., Li, B., Asundi, A.K. Signature Optical Cues: Emerging Technologies for Monitoring Plant Health. Sensors. 2008; 8 3205-3239;

[114] Gruere G.P. Implications of nanotechnology growth in food and agriculture in OECD countries. Food Policy. 2012; 37 191-198.

[115] Hajirostamlo, B., Mirsaeedghazi, N., Arefnia, M., Shariati, M.A., Fard E.A. The role of research and development in agriculture and its dependent concepts in agriculture [Short Review]. Asian J. Appl. Sci. Eng. 2015; 4 1010-1016.

[116] Mukhopadhyay, S.S. Nanotechnology in agriculture: prospects and constraints. Nanotechnol. Sci. Appl. 2014; 7 63-71.

[117] Prasad, R., Kumar, V., Prasad, K.S. Nanotechnology in sustainable agriculture: present concerns and future aspects. Afr. J. Biotechnol. 2014; 13 705-713.

[118] Nicewarner-Pena, S.R., Carado, A.J., Shale, K.E., Keating, C.D. Barcoded Metal Nanowires: Optical Reflectivity and Patterned Fluorescence. The Journal of Physical Chemistry B. 2003; *107* (30) 7360-7367.

[119] Li, Y., Cu, H.Y.T., Luo, D. Multiplexed detection of pathogen DNA with DNA-based fluorescence nanobarcodes. Nat Biotechnol. 2005; 23 885-889.

[120] Lin, C., Jungmann, R., Leifer, A.M., Li, C., Levner, D., Church, G.M., Shih, W.M., Yin, P. Submicrometre geometrically encoded fluorescent barcodes self-assembled from DNA. Nat Chem. 2012; 4 832-839.

[121] Yao, K.S., Li, S.J., Tzeng, K.C., Cheng, T.C., Chang, C.Y., Chiu, C.Y., Liao, C.Y., Hsu, J.J., Lin, Z.P. Fluorescence silica nanoprobe as a biomarker for rapid detection of plant pathogens. Adv. Mater. Res. 2009; *79* 513-516.

[122] Singh, S., Singh, M., Agrawal, V.V., Kumar, A. An attempt to develop surface plasmon resonance based immunosensor for Karnal bunt (*Tilletia indica*) diagnosis based on the experience of nano-gold based lateral flow immuno-dipstick test. Thin Solid Films. 2010; *519* 1156-1159.

[123] Frasco, M.F., Chaniotakis, N. Semiconductor quantum dots in chemical sensors and biosensors. Sensors. 2009; *9* 7266-7286.

[124] Algar, W.R., Krull, U.J. Quantum dots as donors in fluorescence resonance energy transfer for the bioanalysis of nucleic acids, proteins, and other biological molecules. Anal. Bioanal. Chem. 2008; *391* 1609-1618.

[125] Rad, F., Mohsenifar, A., Tabatabaei, M., Safarnejad, M.R., Shahryari, F., Safarpour, H., Foroutan, A., Mardi, M., Davoudi, D., Fotokian, M. Detection of Candidatus Phytoplasma aurantifolia with a quantum dots fret-based biosensor. J. Plant Pathol. 2012; *94* 525-534.

[126] Safarpour, H., Safarnejad, M.R., Tabatabaei, M., Mohsenifar, A., Rad, F., Basirat, M., Shahryari, F., Hasanzadeh, F. Development of a quantum dots FRET-based biosensor for efficient detection of Polymyxa betae. Can. J. Plant Pathol. 2012; *34* 507-515.

[127] Kuila, T., Bose, S., Khanra, P., Mishra, A.K., Kim, N.H., Lee, J.H. Recent advances in graphene-based biosensors. Biosens. Bioelectron. 2011; *26* 4637-4648.

[128] Perez-Lopez, B., Merkoçi, A. Nanoparticles for the development of improved (bio) sensing systems. Anal. Bioanal. Chem. 2011; *399* 1577-1590.

[129] Shiddiky, M.J., Torriero, A.A. Application of ionic liquids in electrochemical sensing systems. Biosens. Bioelectron. 2011; *26* 1775-1787.

[130] Cao, X., Ye, Y., Liu, S. Gold nanoparticle-based signal amplification for biosensing. Anal. Biochem. 2011; *417* 1-16.

[131] Mandler, D., Kraus-Ophir, S., Self-assembled monolayers (SAMs) for electrochemical sensing. J. Solid State Electrochem. 2011; *15* 1535-1558.

[132] Umasankar, Y., Ramasamy, R.P. Highly sensitive electrochemical detection of methyl salicylate using electroactive gold nanoparticles. Analyst. 2013; *138* 6623-6631.

[133] Boonham, N., Glover, R., Tomlinson, J., Mumford, R. Exploiting generic platform technologies for the detection and identification of plant pathogens. In *Sustainable Disease Management in a European Context*; Springer: Berlin, Germany, 2008; 355-363.

[134] Chartuprayoon, N., Rheem, Y., Chen, W., Myung, N. Detection of plant pathogen using LPNE grown single conducting polymer Nanoribbon. In *Meeting Abstracts*; The Electrochemical Society: Pennington, NJ, USA, 2010.

[135] Vermeir, S., Nicolai, B.M., Verboven, P., Van Gerwen, P., Baeten, B., Hoflack, L. Microplate differential calorimetric biosensor for ascorbic acid analysis in food and pharmaceuticals. Analytical Chemistry. 2007; 79, 6119-6127.

[136] Lupetti, K.O., Vieira, I.C., Fatibello-Filho, O. Jack fruit-capric acid biosensor for total phenols determination in wastewaters. Analytical Letters 2004; 37 1833-1846.

[137] Verma, N., Singh, A.K., Kaur, P. Biosensor based on ion selective electrode for detection of L-arginine in fruit juices. Journal of Analytical Chemistry. 2015; 70 1111-1115.

[138] Bontidean, I., Mortari, A., Leth, S., Brown, N.L., Karlson, U., Larsen, M.M. Biosensors for detection of mercury in contaminated soils. Environmental Pollution. 2004; 131 255-262.

[139] Srivastava, S., Ali, M.A., Umrao, S., Parashar, U.K., Srivastava, A., Sumana, G. Graphene oxide-based biosensor for food toxin detection. Applied Biochemistry and Biotechnology. 2014; 174 960-970.

[140] Davis, H.T., Aelion, C.M., Liu, J., Burch, J.B., Cai, B., Lawson, A.B. Potential sources and racial disparities in the residential distribution of soil arsenic and lead among pregnant women. The Science of the Total Environment. 2016; 551-552,

[141] Oliveira, H. Chromium as an environmental pollutant: Insights on induced plant toxicity. Journal of Botany. 2012; 1-8

[142] Wyszkowska, J., Borowik, A., Kucharski, M., Kucharski, J. Effect of cadmium, copper and zinc on plants, soil microorganisms and soil enzymes. Journal of Elementology. 2013; 18 769-796.

[143] Bhalerao, S.A., Sharma, A.S., Poojari, A.C. Toxicity of nickel in plants. International Journal of Pure and Applied Bioscience. 2015; 3 345-355.

[144] Tekaya, N., Saiapina, O., Ouada, H.B., Lagarde, F., Namour, P., Ouada, H.B. Bi-Enzymatic conductometric biosensor for detection of heavy metal ions and pesticides in water samples based on enzymatic inhibition in arthrospira platensis. Journal of Environmental Protection. 2014; 5 1-13.

[145] Zuo, X., Zhang, H., Zhu, Q., Wang, W., Feng, J., Chen, X. A dual-color fluorescent biosensing platform based on WS2 nanosheet for detection of Hg2+ and Ag+. Biosensors and Bioelectronics. 2016; 85 464-470.

[146] Rigo, A.A., Cezaro, A.M.D., Muenchen, D.K., Martinazzo, J., Manzoli, A., Steffens, J., Steffens, C. Heavy metals detection in river water with cantilever nanobiosensor. Journal of Environmental Science and Health. 2020; 36 (4) 1429-1437.

[147] Chen, H., Yada, R. Nanotechnologies in agriculture: new tools for sustainable development. Trends Food Sci Technol. 2011; 22 585-594.

[148] Berekaa, M. Nanotechnology in Food Industry; Advances in Food processing, Packaging and Food Safety, Int.J. Curr. Microbiol. App. Sci. 2015; 4(5) 345-357.