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Development and applications of nanobiosensors for sustainable agricultural and food industries: Recent developments, challenges and perspectives

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ABSTRACT

The increasing global population and limited natural resources are amongst major challenges in the sustainability of agricultural and food industries, together with the rapid shrinking of land and increasing production cost. Based on the application of nanobiosensors, natural resources can be utilised more efficiently. Particularly, nanobiosensors can be used in a wide range of applications throughout the agri-food route, ranging from detection of soil condition, crop diseases caused by pest/pathogen, management of severe infections, and diagnostic tools for detection of pests during storage and ensures final quality assurance. Here, we review the various recent applications of nanobiosensors in agricultural and food industries. The advantages and limitations are also discussed to provide useful insights to both academic and industrial researchers. Moreover, recent patents have been discussed to provide the latest trends in biosensors for agri-food industry to maintain sustainable development.

1. Introduction

The global population is expected to reach 8.5 billion by 2030 with an exponential level rise anticipated to reach 9.8 billion mark by 2050 creating problems in the requirement of natural resources and food production (Alvarado et al., 2019; Marchiol, 2018). Other important challenges are shrinking land space, scarcity of food and crops, competition for natural resources as well as emphasis to increase crop production in adverse environmental conditions (Alvarado et al., 2019). Moreover, contamination of food with microorganisms during storage and processing is another problem raising concern globally. Hence, there is an urgent need to develop novel sustainable methods and/or techniques which can be used by agriculture and food industries to improve the efficiency of natural resources as well as plant hormones, a wide variety of pathogens, herbicides, fertilisers, and metal ions used in producing agricultural and food products. Recently, nanotechnology is providing advanced functional materials to invigorate the existing practices used in the agri-food industries. Various methods such as physical, chemical, and biological routes have been employed for the synthesis of nanomaterials (Selim et al., 2020; Purohit et al., 2019; Mazhar et al., 2017). Applications of unique properties of nanomaterials have been employed to improve the existing conventional technologies. Nanomaterials integration with the

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biosensors, so-called nanobiosensors, has improved the sensing capabilities for a plethora of environmental applications. Thus, development of robust, real time sensing of nanobiosensors by employing unique properties of nanomaterials in association with highly specific biological materials is a better alternative for easy, early diagnosis, and detection of plant diseases (Kaphle et al., 2018; Chamundeeswari et al., 2019).

Nanobiosensors are non-invasive, sensitive, and specifically designed sensors manufactured using novel nanobiotechnology approaches (Kalyani et al., 2021). The real-time responsive signals produced by nanobiosensors can be readily collected and analysed (Omara et al., 2019; Srivastava et al., 2018). The nanobiosensors involve various nanomaterials such as nanotubes, nanowires, nanoparticles, nanocrystals, and nanocomposites. Applications of nanobiosensors may range from detection of sufficient natural resources in ecosystems such as quality of soil and available ground water (Kuswandi, 2019; Khiyami et al., 2014). In the agricultural industry, these small, compact and portable devices can allow the farmers to monitor and control the soil conditions on-site. Nanobiosensors have been used to analyse the fertility, pH, moisture content, mineral concentrations, detection of pests and deficiencies of minerals in the soil before the onset of diseases. Rai et al. (2015) and Sekhon (2014) reported the use of nanobiosensor to analyse the moisture, fertility and growth hormone concentration to check the soil productivity. Similarly, in Ramnani et al. (2016) study, single-walled carbon nanotubes and nanowires as nanobiosensors were used to improve the soil conditions. The market size of biosensors has reached US $15.5 billion in 2015 (https://www.grandviewresearch.com/industry-analysis/biosensors-market) and it is expected to expand to approximately US$ 26.9 billion by 2020. Network of nanobiosensors can estimate the yield and detection of various diseases during crops in the fields. Recently, there are various proposals to associate these nanobiosensors with information technology to disseminate the result to remote areas so the farmers in the far-off areas can be benefited (Duhan et al., 2017; Srivastava et al., 2018). On the other hand, the application of nanobiosensors in the food industry is growing fast, too. For instance, nanobiosensors have been used in the food industry to ensure food safety during the production and packaging (Sridhar et al., 2021; Neethirajan et al., 2018) and detect allergens and/or pathogens. In case of the food industry, various other challenges exist such as food security, safety, availability and utilisation (Calicioglu et al., 2019; Dasgupta et al., 2017). Thus, nanobiosensors exhibit superior attributes such as easy operations, high sensitivity along with rapid detection for pesticide residues as compared to conventional HPLC and GC–MS.

In this review, recent applications of nanobiosensors in agricultural and food industries are critically discussed along with their challenges and perspectives.

2. Nanomaterials for nanobiosensors

Nanobiosensor is comprised of three components namely biological probe including affinity-based material such as antibody–antigen interactions, enzyme–substrate interactions, nucleic acid interactions, and cell-based interactions; transducer that converts the biological signals into digital ones, and data recording unit that involves storing and transfer of the data (Verma and Rani, 2021). Biological component can be DNA, enzyme, antibodies, biomimetic, and aptamers. Natural biological components have been replaced by synthetic receptors to mimic the functions with more rapid and specific detection range (Neethirajan et al., 2018). Analytes can be detected by the biological probes combined with various nanoparticles such as metallic, magnetic, quantum dots, graphene oxide, and carbon nanotubes. Transducers using electrochemical signals are amperometric, voltametric, potentiometric, and optical signals including colorimetric, surface Plasmon resonance, metallic fluorescence, and optical fibres (Shawon et al., 2020; Verma, 2017). Different types of advanced material have been employed for nanosensing applications for development of nanobiosensors (Fig. 1). Carbon nanotube-based nanomaterials, single walled carbon nanotubes (SWCNTs) and multiwalled carbon nanotubes (MWCNTs), have been used for the development of nanosensor. Carbon based nanomaterials has proved to be better surface for immobilising biological component in the biosensors (Verma et al., 2019). It imparts mechanical and physical properties to improve conductive properties and temperature resistance. But major limitation in this case is less solubility of these nanomaterials in aqueous environment. Some other challenges are lack of selectivity along with sustainability of nanostructures, fabrication of nanobiosensors, and toxicity (Naresh and Lee, 2021). Other materials used include fullerenes, titanium, and silicon oxides (Marchiol, 2018). Polymers such as zeolites, chitosan, and polyacrylic acid can be used for encapsulation purposes. Different metallic nanoparticles usually consisting of gold and silver can be used for nanobiosensors owing to their safer properties. Gold and silver-based materials are most widely used in food nanobiosensors for detecting contaminants and pathogens in food and water.

Detection of pathogenic contaminants can be done with metallic components based nanobiosensor on provision of being safer alternatives in the food items (Oluwaseun et al., 2018). Another most common material for fabrication of nanobiosensor is based upon measuring fluorescence. Fluorescence based nanobiosensors use two methodologies for sensing; one of them is quantum dots sensors on the basis of semiconducting properties and the other one is based upon fluorescence resonance energy transfer (FRET) intermolecular charge transfer (ICT). The fluorescence-based detection can give easier alternatives of detection (Girigoswami and Akhtar, 2019). Some other strategies such as one fluorophore, two fluorophores, and modular designs have been employed for the design of fluorescent based biosensors. However, a major drawback with fluorescence-based biosensors is the high cost involved that can be resolved by using metal enhanced fluorescence (MEF) strategy. The next important metallic counterpart used in fabrication of nanosensor is zinc oxide (ZnO). Nanobiosensors are based upon light emitting diodes (LEDs) that are used for detection of free radicals in food packaging materials. The salient properties of ZnO include high catalytic power, high isoelectric point, and strong adsorption capability (Malhotra and Mandal, 2019).

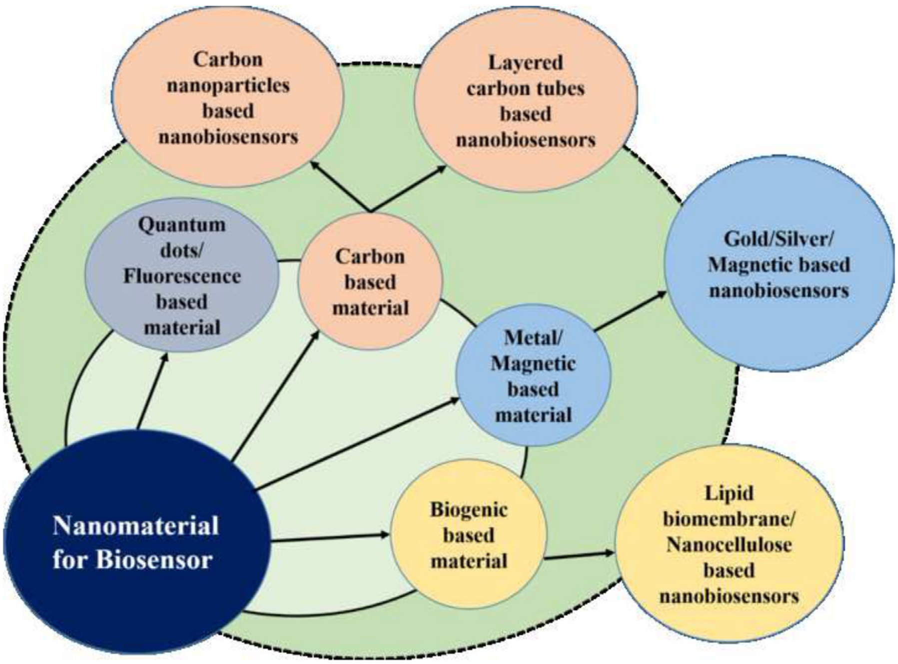

Fig. 1. Advanced functional nanomaterial for fabrication of nanobiosensor. Detailed classification gives insight into nanomaterials that can be used in nanobiosensors.

Magnetoelastic is novel material comprising magnet with gold nanoparticles. Magnetic nanomaterial can provide advantage of easy separation and avoid non-specific binding of the biological molecules that reduces the signal to noise ratio. These involve three classifications with different properties such as oxides, metals and alloys. Some advancements include microfluidics approach including nanotechnology, biosensing, and microsystems at microscale values (Escarpa, 2014). These microfluidics strategies have been used to sense the foodborne allergens, pathogens toxins, and other contaminants (Weng and Neethirajan, 2017). However, the fabrication at miniaturised scale remains a major challenge along with electrokinetic and hydrodynamic flows. The challenges can be overcome by integrating DNA into microfluidic systems. Another strategy is to combine microfluidic approach along with cell morphology to facilitate food safety (Arduini et al., 2019). Biological components have been used as substitutes of metals and other materials in fabrication of nanobiosensors. One such material is bilayer lipid membranes. Most of lipid membrane based nanobiosensors have been constructed and used for detection of metals, toxins, and microorganisms. Some of the technical problems are associated such as less stability and their sensitivity to damage outside the electrolyte solutions. Their stability can be improved by using glass, ZnO and graphene to strengthen the stability of membranes (Nikoleli et al., 2018).

Agricultural wastes can be used as novel material for nanobiosensors on account of their abundance in the environment and an inexpensive alternative. Nanocellulose fibres have been fabricated and can be employed for diverse applications (Shen, 2017; Tijani et al., 2016). Rice husk can also be used for developing nanobiosensors which is considered as waste/by product of rice milling. Rice husks can be assimilated with silica that can have better applications. These materials have been frequently used for agricultural practices (Marchiol, 2018). This type of materials has been efficient for various applications but major problem is high cost involved in their design and processing.

Thus, different types of the nanomaterials ranging from the expensive to cost-effective agricultural waste sources have been integrated for the design of the robust nanobiosensor.

3. Application of nanobiosensor in the agricultural industry

In case of agricultural practices, new techniques are required for maintaining sustainability and it includes nanobiosensors due to their improved sensitivity and specificity over conventional methods. Some complications involved with conventional techniques such as limited number of samples handled in time, interference with various matrices and long-time intake for analysis can be resolved by using nanobiosensors (Table 1). Thus, nanobiosensors provide an efficient detection with greater precision, continuous monitoring with less time and cost involved (Zamora-Sequeira et al., 2019). Excessive use of pesticides and chemicals resulted in unsustainability of agriculture and food. Use of nanotechnology based agricultural practices has resulted in improved yield (Singh et al., 2021). Another extensive study on use and application of biosensors has been carried out (Griesche and Baeumner, 2020).

Table 1
Different types of nanobiosensors in agriculture. Trend in development of nanobiosensor for agriculture has witnessed growth ranging from specific detection of pathogens, mycotoxins, signalling molecules through reduction in time of detection.

Nanobiosensor	Nanomaterial used	Sensor type	Applications	Advantage (LOD, cost/time)	Reference
Quantum dot nanosensor	Gold particles	Immunobased sensor	Detection of mycotoxins ZEA, DON, FB1/FB2 in corn oats and barley	Maize Don 80 µg/Kg, Wheat Don 400 µg/Kg, 5 min	Lattanzio et al. (2012)
QD nanosensor	Quantum dots	Fluorescence	Detection of pathogens	–	Esker et al. (2018)
QD nanosensor	Quantum dots	Fluorescence	*Phytoplasma aurantifolia*	5 ca/µL	Rad et al. (2012)
DNA nanobiosensor	Carbon nanotubes	Immunosensor	*Ganoderma boninse* for infection of palm oil tree	–	Safarpour et al. (2012)
Surface plasmon resonance	Multiwalled carbon nanotubes	SPR	Detection of Cymbidium Mosaic virus	–	Antonacci et al. (2017)
Artificial nose	Carbon nanomaterials	Volatile organic compound profile	Detection of pathogens depending on the organic compounds released	30 min with 80%–90% accuracy	Cui et al. (2018a,b)
AChE biosensor	Single and Multiwalled carbon nanotubes	electrochemical	Detection of pesticides methylparathion, parathion and paraoxan	0.4 pM highly sensitive	Wong et al. (2017)
	DNA based biosensor	Electrochemical	Detection of *Phytophthorapulmivora* causing black pod rot in cacao pod	–	James et al. (2019)
	Calcium phosphate	Electrochemical	Pathogenic detection	0.30 ng/ml	Manjunatha et al. (2016)
Pesticide detection nanobiosensor	Graphene based with molecular imprinted polymers	Electrochemical	Pesticide detection of chlorothlonil and chlorpyrifos methyl	0.13 mg/L with very cost-effective technology @ $2 per 100 mm^2	Xu et al. (2020)
Molecular imprinted polymer based	Mesoporous molecular sieves embedded with carbon dots CDs@SBA15@MIP	Electrochemical	Detection of kaempferol polyphenol in vegetables	14 µg/L with single step method	He et al. (2020)
Plant hormone nanobiosensor	Receptor DAD2 from Petunia hybrid and HTLT from *Striga hermohthica* with green fluorescent protein	Fluorescent based	Detection of strigolactones as signalling molecules for plant growth and parasitism	High throughput screening method	Chesterfield et al. (2020)
Smart nanobiosensor	Zinc oxide and Copper	Electrochemical	Enhance the germination of tomato chili and cucurbits in Mexico	50 ppm	Negrete (2020)
Acetylcholinesterase immobilised on copper oxide	Cholinergic enzyme	Square wave voltammetry	Detection of malathion	0.31 ng/L in 10 min	Bao et al. (2019)
Acetylcholinesterase E on titanium oxide	Cholinergic enzyme	Differential pulse voltammetry	Detection of dichlorvos	6.4 µg/mL, 25 min	Cui et al. (2018a,b), Mishra et al. (2021)
Acetylcholinesterase	Cholinergic enzyme	Amperometric	Detection of chlorpyrifos	0.01 µg/L, 12 min	Hou et al. (2019)
Acetylcholinesterase onto polymeric surface and silver	Enzyme	Amperometric	Detection of Malathion	0.001 µg/L	Zhang et al. (2019)
Acetylcholinesterase with multiwalled carbon nanotubes	Enzyme	Differential pulse voltammetry	Detection of paraoxon	1.1 ng/mL, 12 min	Mahmoudi et al. (2019)
Acetylcholinesterase on white paper using indophenol acetate	Enzyme	Coloured reaction	Detection of chlorpyrifos	3.3 µg/L, 10 min	Fu et al. (2019)

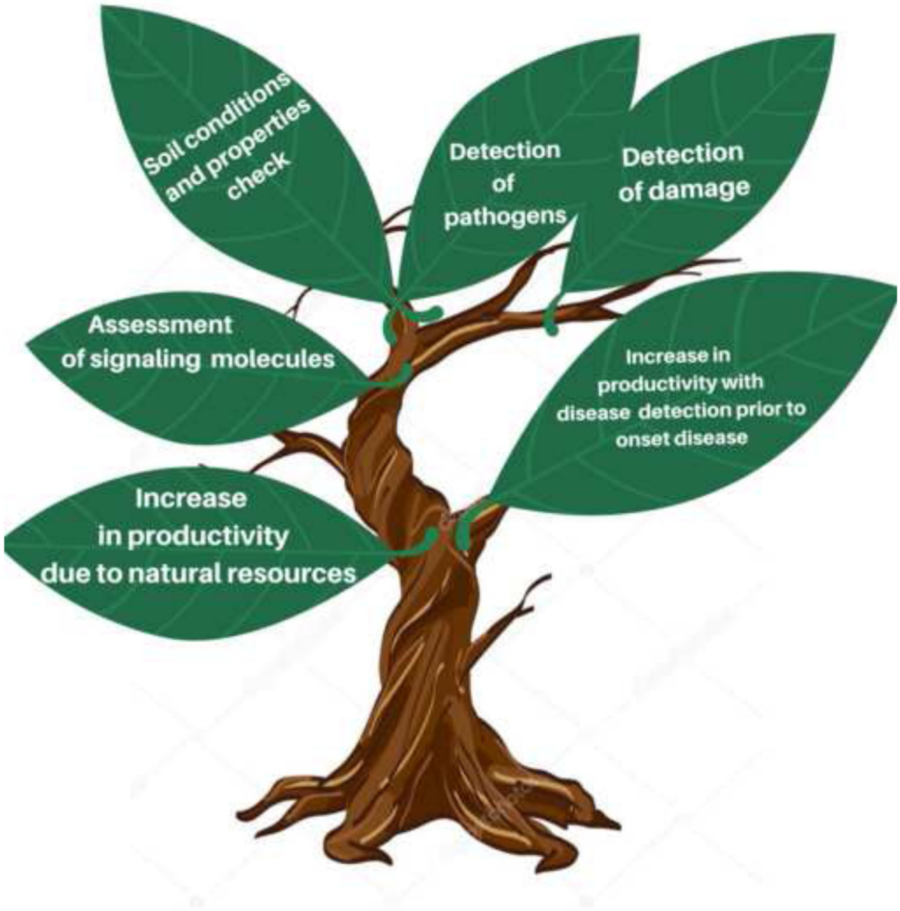

Fig. 2. Applications of nanobiosensor in Agriculture. Range of nanobiosensors used in agriculture sector from increase in productivity better use of resources and detection of disease before onset leading to easy management of crop diseases.

There are various applications of nanobiosensors in developing novel methods for sustainable agricultural practices (Fig. 2). Nanobiosensors may be based upon gross and massive response of crop in whole field depending upon smart sensing, precise response based on nanobionics approach. Nanobionics are the mathematical based models of sensors to sense the fluxes of various phytohormones/signalling molecules (Butnariu and Butu, 2019). In general, the use of nanobiosensors has been contributing to the growth of ''smart agriculture'' and/or ''precise farming'', due to their ability to sense, process and detect the changes (Manjunatha et al., 2016). Precision Farming gives a detailed account on the information collected from field or soil condition for accurate decision to achieve maximum yield with reduced inputs of chemical fertilisers and pesticides. Moreover, smart plant systems help in rapid analysis and efficient management of costly agrochemicals, environmental abiotic stress and phytopathogens which are responsible for major crop losses. Regular monitoring of plants is a tedious process that can be carried out precisely using smart nanobiosensors (Mittal et al., 2020). Recently, Alvarado et al. (2019) suggested integrating nanobiosensors with information technology to benefit the farmers in remote areas. Advancement in the sensing system can be achieved by connecting the nanobiosensor with global positioning system which could really help farmers in remote areas to manage the fertilisers, pesticides, insecticides, water levels, physical and chemical stresses as well as pathogen detection to prevent onset of many diseases ahead of time in on site crops in the fields (Shang et al., 2019).

3.1. Detection of pest/pathogen in the plants

Phytopathology is the branch of science which aims to detect pathogens. In the starting years, the detection of specific pathogens mainly depended on their visualisation and it usually took several days (Khiyami et al., 2014). Early detection of pathogens with novel biosensing approaches lead to management of disease and thus less productivity losses. The precise identification of pathogens can assist in developing treatment strategies to combat diseases (Ali et al., 2021). However, with the aid of nanobiosensors, the detection can be completed within less time as compared to conventional methods.

This novel diagnostic procedure is also known as nanodiagnostics. Nanobiosensors were used to detect contaminating pathogens. Gold nanoparticles based nanobiosensors were employed for the diagnosis of agroterrorism agents (Acharya and Pal, 2020). The nanoparticles-based sensors containing gold particles have been developed for noting the plant pathogens. Biological component involved is DNA in most nanobiosensors. Moreover, these nanobiosensors can help monitor the interaction of plants with pathogens, pathogen population genetics and gene transfer between pathogens and host. Khiyami et al. (2014) used nanobiosensors to forecast the plant disease as well as the detection of mycotoxin.

Nanopore sensor is a technique employed to sequence the DNA in a fast and accurate way. Nanopore platform which monitors the travel of DNA through nanopore has been developed in which pathogen detection can be performed by studying the genome (Ozsolak, 2012). Detection of pathogenic bacteria using real time polymerase chain reactions have been successfully employed (Jyoti and Tomar, 2017). Nanobiosensors with increased sensitivity can enhance and improve food safety in agriculture. Fibre optic probes immobilised with antibodies have been used for detection of *E. coli.* This has resulted in a major advantage that is less time (20 min) for detection of bacteria and fungi (Khiyami et al., 2014). Detection of *Phytophthora palmivora* causing black pod rot in cacao pods can be performed using electrochemical detection with DNA based nanobiosensor. Sandwich hybrids have been used with oligoprobes based on its sequence of *Phytophthora palmivora* with genomic DNA (James et al., 2019). The nanobiosensor has been found to have higher sensitivity up to 0.30 ng DNA/μL (James et al., 2019) Similarly, biosensor containing silica with fluorescent probes as nanoparticles immobilised with antibody against pathogen have been prepared to detect the *Xanthomonas axonopodis,* a causative agent of tomatoes and peppers (James et al., 2019). Another alternative for fabrication of nanobiosensors can be nanocomposites comprising calcium phosphate and phosphate with fluorogenic substrates as phosphorus is one of the major components in cell-based processes such as cell division, cellular signal transduction, and membrane synthesis (Caon et al., 2017). Detection time has been reduced from 210 min to 30 min. Rapid detection of various plant pathogens can be performed using nanobiosensors (Caon et al., 2017). Copper oxide can be used to detect *Aspergillus niger*. Normal difference in vegetative index sensor can be used to convert signal into light emitting diode. This biosensor can sense the absorption of more red light that indicates the healthy plants (Srivastava et al., 2018).

Nanobiosensors using quantum dots fluorescence resonance energy transfer phenomenon has been used for diagnosis of *Phytoplasma aurantifolia* causing witches broom disease in lemon plants. Immunosensor approach has been used to increase sensitivity to 100% (Duhan et al., 2017). Metallic nanoparticle based nanobiosensors have a wide range of biorecognition elements and are most commonly employed. Gold nanoparticles-based immunosensors were also reported to detect *Cymbidium mosaic virus* and *Odontoglossum ringspot virus* in the orchids, based on the surface plasmon resonance phenomenon of these particles (Jian et al., 2018). Similarly, these detections can also be associated with a global positioning system for a continuous, effective and remote control of plant pests (Antonacci et al., 2017). Kaushal and Wani (2017) reported the use of microarray based-nanochips for the detection of plant pathogens, with the superiority of specificity and sensitivity. Nanochips have been developed for microarray that consist of fluorescent capture probes to detect single nucleotide change in bacteria and viruses. In this case electrochemical signal was obtained by reaction of antibody with *Vibrio parahaemolyticus* causing Karnal bunt disease in wheat (Kaushal and Wani, 2017).

Based on the comparison of volatile organic compounds (VOCs) profiles with the one secreted by the plants in the absence of the damage, the damage can be signified. In Spinelli et al.'s work, 88% accuracy was observed to detect the infection of *Agrobacterium vitis* in grapevines and tomato plants, based on the comparison of the VOC profiles collected from infected and healthy plants (Spinelli et al., 2012). The fire blight pathogen (*Erwinia amylovora*) is able to impart some unique VOCs which can be easily differentiated with the accuracy of 88% (Spinelli et al., 2012). In Fuentes et al.'s study (2018), the fire and blossom blight associated with the infection of *Pseudomonas syringae* and *Erwinia amylovora* in the apple trees were successfully detected in both laboratory and field (Fuentes et al., 2018). Changes in common agricultural practices has resulted in food loss and lab-on-chip based novel technology has been developed for rapid detection of *Xylella fastidiosa,* a causative agent of grapevine leafroll virus 3, resulting epidemic in Puglia. Lab-on-chip method require less sample volumes providing real time rapid detection at low cost with more portability (Buja et al., 2021)

The identification of damaged tomato plants by the attack of spider mites (*Tetranychu surticae* Koch), tomato plant by planthopper (*Nilapava talugens*) and rice plants attacked by striped rice stem borer (*Chilo suppressalis*) were reported (Xu et al., 2014).

Nanobiosensor using nanodiagnostic approaches have been fabricated by using metallic nanoparticles with improved speed of detection (Shoala, 2019). Nanobiosensors can help increase agricultural produce by employing nanotechnology integrated with the internet, neural networks and artificial vision to develop smart delivery systems for distribution of nutrients (Negrete, 2020). This strategy has been used in developing the smart technology for distributing sodium selenite in ruminants, zinc oxide, copper, and iron in soil ($\leq$50 ppm) to improve and uplift Mexican agriculture system. This has helped in the increase in germination of tomato, chilli, and cucurbits (Rodrigues et al., 2018). One important challenge is the inability of nanobiosensor in detection of asymptomatic plants (Ali et al., 2021).

3.2. Detection of pesticide residues in the plants

Pesticides are the chemical compounds which aim to control the pest's population, thus improving the agricultural productivity by minimising the loss. During the growth of the plants, various pesticides with different doses are usually applied. However, the pesticide residue in agricultural products can be a chemical hazard for the food industry due to their toxicity (Zhao et al., 2015). Moreover, detection of concentration of pesticide on the plants can also prevent the overuse of pesticides and help in management of pesticides on the field. Therefore, pesticide detection is always an important component of the hazard analysis critical control points parameter during the food production and it is drawing research attention from both academic and industrial sides.

Various detection techniques such as biosensors using surface Plasmon resonance, enzymatic sensors equipped with acetylcholinesterase using multiwalled carbon nanotubes and/or single-walled carbon nanotubes have been developed to detect various pesticides such as methyl parathion, parathion, fenitrothion and paraoxon (Sun et al., 2014; James et al., 2019). For example, gold nanoparticle-based biosensor has been successfully developed to detect chlorpyrifos and carbofuran at 0.06 and 0.08 $\mu g/dm^3$, respectively (Sun et al., 2014). Du et al. (2019) reported the detection of detect carbaryl, monocrotophos and methyl parathion using quantum dots-based nanobiosensors with colloidal gold nanoparticles equipped with immunofluorescence to sense 2,4-D the content up to 250 pg/L.

Acetylcholinesterase based nanobiosensor have been fabricated containing iron nanoparticles using chitosan (Rodrigues et al., 2018). Voltage based analysis has been performed and malathion has been detected in pond water and tomato samples with limit of detection (0.3 mmol/L) associated with higher level of sensitivity (Rodrigues et al., 2018). Another enzyme based nanobiosensor involved a combination of butyrylcholinesterase, alkaline phosphatase, and tyrosinase using Prussian blue nanoparticles immobilised using origami paper. This has been used for detection of various pesticides such as atrazine, paraoxon, and 2,4-dichlorophenoxyacetic acid. This sensor produced the signal based on a potentiometric approach to provide paper based nanobiosensor that can strengthen the approach of development of portable nanobiosensors (Arduini et al., 2019).

Various herbicides, insecticides and pesticides can be detected with the most commonly used approach of electrochemical sensors. One such nanobiosensor has been developed using hollow fibre pencil-based graphite containing multiwalled carbon nanotubes, and CuO nanoparticles. It could detect in situ concentrations of glyphosate with voltammetry approach (Mohammed-Bagher et al., 2018).

Graphene and terahertz based flexible sensors with robust sensing and low cost (> $2) have been developed to detect pesticides at biological interfaces (Xu et al., 2020). This sensor detected chlorpyrifos methyl and chlorothalonil with the limit of detection 0.13 mg/L and 0.60 mg/L, respectively. Moreover, less fabrication step ensures the less cost, commercialisation of this device for pesticide detection (Xu et al., 2020). Single step analysis is the most preferred method as compared to multistep processes for sensing and detection as time of analysis is significantly lesser. A similar nanosensor has been developed using nanocomposites containing mesoporous molecular sieves embedded with carbon dots for fabrication of molecular imprinted polymers capable of detecting concentration of Kaempferol in vegetables for analysing anticancer properties (He et al., 2020).

3.3. Evaluation of soil quality

In agriculture, soil quality is one of the most important factors to be evaluated for pH, nutrients, and moisture content prior to all agricultural practices. Monreal et al. (2015) suggested the quality of the soil can be evaluated, based on the interaction between microorganisms in the rhizosphere and the biosensor. In Kaushal and Wani (2017) study, intelligent fertiliser such as zinc fertilisers with nanoparticles was developed to achieve the controlled-release of the fertiliser to the plant roots and sense the feedback while microelectromechanical system (MEMS) was developed to detect the soil quality using microelectronic circuits (Kaushal and Wani, 2017).

Strigolactones are plant hormones released in the rhizosphere as signalling molecules that ensure the key role in plant development and plant parasitism. Fluorescent based nanosensor containing strigolactone receptors DAD2 from *Petunia hybrid* and HTLT from *Striga hermonhthica* embedded with green fluorescent protein have been developed for detection and high throughput screening of agrochemical compounds such as strigolactone and its signalling pathways in plants (Chesterfield et al., 2020) Moreover, ferric sulphide nanoparticles with agglomeration and sponge like dried structures are produced using green synthesis. The Fourier transform infrared spectroscopy has confirmed the presence of iron and sulphur in the nanomaterial that can enhance agricultural production by using these nanofertilizers (Pavithra et al., 2020).

3.4. Other applications of nanobiosensors

Besides above-mentioned applications, nanobiosensors can also be used to measure the concentration of signalling molecules produced by plants (Kwak et al., 2017). For example, small molecule nanobiosensors such as strigolactones were used to detect the signalling hormone which inhibits the plant shoot branching. Phytoestrogens are naturally present in several plants such as soybeans, fruits, and cabbages. They are produced by plants in their defence system against damage caused by fungi and they are known as dietary estrogens. So far, FRET probe using fluorescence signals and estrogen binding domain has been developed to detect the phytoestrogens such as genistein, daidzein, and resveratrol. Because dopamine and catecholamine play important roles in plant growth, development, and synthetic pathways. Nanobiosensors were employed to detect the levels of dopamine (Wong et al., 2017). Similarly, Tsuchiya et al. (2015) developed a fluorescence turn-on probe using Yoshimu lactone green to detect strigolactone molecules. Moreover, real time sensing can be coupled with automation and management of natural resources in a better way. The automation of irrigation systems using sensor technology has great potential for efficient use of water which is one of the major natural resources required for sustainable agriculture in future (Ramnani et al., 2016).

Table 2
Different types of nanobiosensor in food industry. Nanobiosensors in food industry has been used for detection of any contaminants during harvesting, storage, transportation, and smart packaging with nanobarcodes for easy detection of pathogens on shelves in supermarkets.

Nanobiosensor	Nanomaterial used	Sensor type	Applications in food industry	Advantage (Limit of detection)	References
Multiple channel nanobiosensor	Carbon nanomaterial	Immunosensor based	Used for checking concentration of sweeteners, sucrose, glucose, cyclamate and saccharin	Glucose 50-150 mM, saccharin 5-15 mM	Zhang et al. (2014)
Array based sensor	Carbon nanotubes	Molecular array based	Screening of genetically modified organisms	–	Arugula and Simonian (2016)
Aptameric sensor	Aptamers	DNA/ peptide less than 25 KDa	Detection of pathogens	5.0 nM	Sharma et al. (2015)
Toxin detection sensor	SWCNTs	Piezoelectric and optic based	Detection of small toxin molecules in food	nM-fM level	Bahadır and Sezgintürk (2017)
Nanosensor	Carbon nanotubes	–	Detection of heavy metals such as arsenic, copper and mercury	5-140μg/L	Pola-López et al. (2018)
Aptamer sensor	Carbon nanomaterial	Aptamer based	Antibiotic traces of acrylamide and carcinogens	10 ng/mL	Li et al. (2015)
Surface plasmon resonance based sensor	Carbon nanomaterial	Cantilever approach	Detection of aflatoxins in peanut and rice	2.5 ppb	Moon et al. (2018)
Viscosity based determination	Magnetic particles	Change in viscosity	Detection of pathogens	–	Sportelli et al. (2018)
Antibiotic residue detection	Gold, platinum and silica	Nanoenzyme conjugate with MIP as biomimetic body	Detection of sulfadiazine	IC15: 0.09 mg and IC50 6.1 mg/L	He et al. (2020)
Melamine detection	DNA-Cu-NPs	Fluorescence based detection	Detection of melamine in milk	50-120 μmol/L	Ga et al. (2020)
Chemosynthetic mimotope peptide sensor	Chemosynthetic peptide	Immunochromato-graphic based	Detection of ochratoxin A	0.187 ng/mL	You et al. (2020)
DNA aptameric sensor	DNA aptamers		Detection of *Campylobacter jejuni*	10 CFU/mL	Chen et al. (2020)
Nanosensor	Sol–gel derived ZnO nanoparticles	β-galactosidase based	Detection of *E. coli*	10^1 CFU/mL	Meraat et al. (2020)
Biofilm and Toxin nanobiosensor	DNA aptamers with Graphite oxide	FRET based	Detection of zearalenone ochratoxin A and biofilms	1.79ng/mL-1.484ng/mL	Wang et al. (2020)
ZIF-8 AuNP/ chitosan	DNA aptamers	Differential pulse voltammetry	Detection of *Bacillus cereus*	3 CFU/mL	Zhang et al. (2019)
Silver and Bovine serum albumin nanoflowers	DNA aptamers	Differential pulse voltammetry	Detection of *E. coli.*	2 CFU/mL Shahvokhian and Ranjbal (2018)	
Carbon nanofibers	DNA aptamers	Square wave voltammetry	Detection of *Vibrio cholerae*	1.25×10^{-13}	Ozoemena et al. (2020)

(*continued on next page*)

4. Application of nanobiosensors in the food industry

The development of novel technology with more robustness and improved sensitivities is always prioritised by the contemporary food industry. As suggested by Neethirajan et al. (2018), nanobiosensor-based techniques are able to sense, process and produce accurate signals (Fig. 3). Nanobiosensors have the advantage of early detection of pathogens, toxins,

Table 2 (*continued*).

Nanobiosensor	Nanomaterial used	Sensor type	Applications in food industry	Advantage (Limit of detection)	References
Magnetic particle chains	Antibody	Sandwich ELISA	Detection of *Salmonella* in chicken	11 CFU/mL, 2.5 h	Zheng et al. (2020)
Carbon nanowires	DNA aptamer	ELISA based	Detection of *Salmonella in chicken*	80 CFU/mL, 2 h	Qiu et al. (2019)
Silver nanoparticles	Urease-antibody	ELISA based	Detection of *Salmonella* in food samples	10^2 CFU/mL, 2 h	Wang et al. (2020)
Iron oxide nanoparticles	Antibody	ELISA based	Detection of *Salmonella* in milk	34 CFU/mL	Cheng et al. (2019)
Sandwich nanoparticles with catalase enzyme	Antibody	ELISA based	*Salmonella* in chicken	35 CFU/mL, 3 h	Guo et al. (2020)
Zinc oxide	Antibody	Sandwich ELISA based	*Salmonella typhimurium*	1.5 h	Huang et al. (2020)

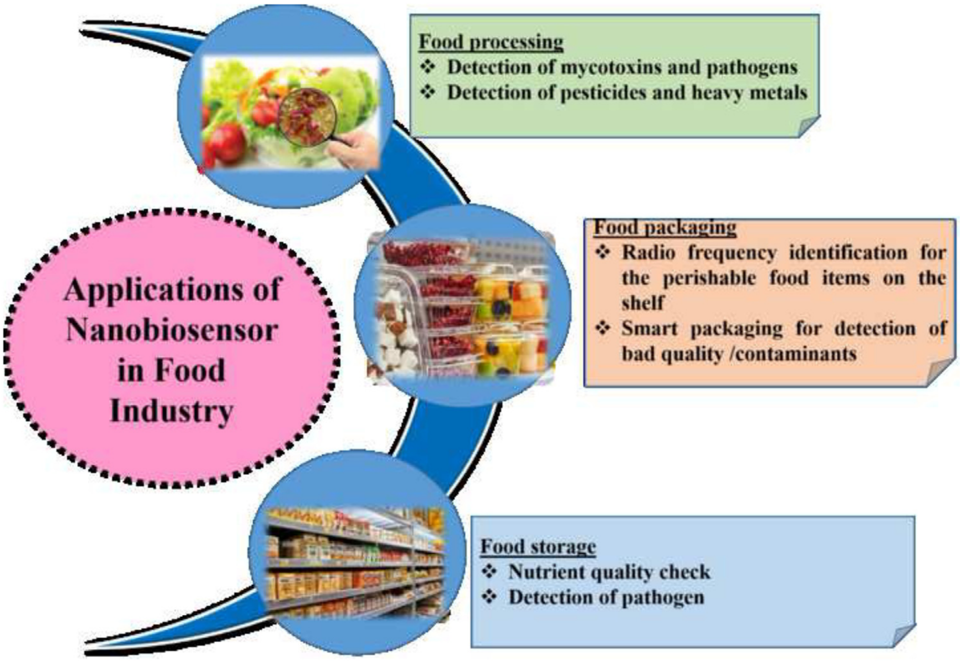

Fig. 3. Applications of nanobiosensor in food industry. Applications of nanobiosensors have been expanding in food industry to meet the potential quality check and early detection of adulterants.

and chemicals during processing and storage. The analytical techniques mainly include detection of change in mass resonance frequency by cantilever, functionalised plasmonic nanoparticles or gold and silver nanoparticles with DNA to detect change in optical properties (Table 2). Various recent methods that have improved the detection includes intelligent packaging, microfluidics and loop mediated isothermal amplification (LAMP). Most of the nanobiosensors developed so far have provided the sensitive solution with an improved limit of detection (Caon et al., 2017). Various aptamers and microfluidic approaches-based nanobiosensors have been developed to meet different requirements by the food industry to detect pathogens, pesticides, heavy metal residues and toxins in order to ensure the quality and safety of the food products. Silver nanoparticles based nanobiosensors with laser ablation detection systems have been developed (Sportelli et al., 2018). Nanoparticles using silver metal have been preferred over other metals on the basis of safety involved. Moreover, very less concentration change can be detected by high energy lasers (Sportelli et al., 2018).

4.1. Control of nutrient value and quality of food products

The nutritional value of the food may compromise due to a wide range of factors including biological, microbiological, chemical, biochemical and mechanical reasons. Specifically, biological and microbiological factors include various contaminants such as bacteria, fungi, mites and insects etc. Various types of reactions (biochemical and chemical) such as Maillard reaction, lipid oxidation or mechanical damage during post-harvest storage. Some other mechanical factors include germination, sprouting and senescence leading to spoilage. Enzyme-based biosensor containing glutamate dehydrogenase and glutamate oxidase has been developed to estimate the concentrations of some toxins such as monosodium glutamate to avoid their neurotoxicity diseases related to human kidney, liver, and brain (Arugula and Simonian, 2016). Advancements in nanobiosensors include multiplex sensing where multiple analytes can be detected in a single step. Zhang et al. (2014) fabricated a nanobiosensor that can detect and measure concentrations of different sweeteners such as sucrose, glucose, cyclamate and saccharin. Nanobiosensors in food supply for detection of genetically modified organisms confirms the diverse applications of nanobiosensors in the food industry (Arugula and Simonian, 2016).

4.2. Detections of pathogen/toxins in food products

Generally, aptamers with molecule weight less than 25 kDa are required in biosensors to detect pathogens. One advantage of using these aptamers in nanobiosensor is its specificity since they can be specifically bounded to bacteria, proteins, viruses, molecules and ions (Sharma et al., 2015). A methylene dye based photoactivated indicator dye has been developed that is used to measure package oxygen leading to detection for pathogens reported a methylene blue dye-based photoactivated indicator ink to detect oxygen content as the indicator of aerobic pathogens growth. So far, various bacteriophage-based nanobiosensors have been developed to detect pathogens like *Staphylococcus aureus* and has been approved by US Food and Drug Agency (Silva et al., 2018).

Majority of fungal and bacterial diseases are associated with the release of toxins that can have serious impacts on human health involving both acute and chronic such as reduction of immunity, alteration in protein metabolism, convulsions, neurotoxicity and liver cancer (Alghuthaymi et al., 2021). So far, electrochemical, optic and/or piezoelectric sensing has been applied to detect the presence of toxin in the food products (Bahadır and Sezgintürk, 2017). Among various toxins in the food products, heavy metal can be a good example. A large number of clinical trials have proved that heavy metals such as arsenic, cadmium, mercury and lead can interfere with metabolic pathways and can have serious impacts (Verma and Kaur, 2016). For this reason, new biosensors equipped with genetically modified bacterial cells and green fluorescent signals were developed to detect the presence of these heavy metals in the food products. For example, Pola-López et al. (2018) developed a biosensor which can detect the arsenic in the content range of 5-140 μg/L. Biosensors have also been applied in the detection of other toxins in various food products such as processing contaminants as acrylamide, acrolein, chloropropanol, biogenic amines and polycyclic amines, as well as the preservatives including benzene, methylimidazole, nitrosamines and semicarbazide (Li et al., 2015). Toxins produced as a result of secondary metabolism in fungi are aflatoxins that can affect the quality of food items including peanuts, almonds and rice. Aflatoxins have been considered as carcinogenic and known to cause hepatic carcinoma. For detection of these toxins, a highly portable nanobiosensor has been fabricated using Plasmon resonance phenomenon (Moon et al., 2018). The response is related to change in mass in presence of aflatoxin that can be detected with surface plasmon resonance approach. In this nanosensor, the limit of detection is 2.5 ppb. Rapid detection of spore based miniaturised assay for aflatoxin in milk samples was successfully demonstrated (Singh et al., 2019). Moreover, the biosensor can be employed for detection of aflatoxin in peanut, almond and rice samples. Despite all desired features, this sensor has some limitations related to reusability of the sensor, cost of fabrication and quantitative analysis of samples (Moon et al., 2018). Aflatoxins synthesised by *Aspergillus flavus*, *Aspergillus parasiticus* that can retard growth in children, decreased immunological system and carcinogenesis in liver (Yan et al., 2020). Country wise permissible limit has been fixed from 2 μg/kg (European Union) to 20 μg/kg (China) and 30 μg/kg (India). Recent trends and advancements in biosensing and role of nanomaterials in detection of aflatoxin have been recently discussed (Bhardwaj et al., 2021). Development of nanotechnology has increased the sensitivity, reproducibility, limit of detection and wide detection range of biosensors (Li et al., 2020). The comprehensive analysis of aflatoxins detection was carried out using 0-dimensional electrochemical nanobiosensor (Ma et al., 2016). Graphene based nanosensors using gold nanoparticles demonstrated aflatoxin limit in the range of 0.1–2.5 ng/mL (Bhardwaj et al., 2019).

Foods contaminated with antibiotic residues effect human health and the permissible limit of so many foods has been fixed. It is necessary to detect the sulfonamide residues in meat and poultry food items. A nanoenzyme labelled immunoassay for detection of sulfadiazine in food residue nanosensor has been developed by He et al. (2020). Gold, platinum and silica have been used for fabrication of nanoenzyme conjugate along with molecularly imprinted polymers as biomimetic bodies. The accuracy of the sensor has been evaluated using enzyme linked immunosorbent assay method for honey and milk with different concentrations of sulfadiazine (0.5–12.5 mg/L). The nanosensor is quite sensitive with limit of detection IC15 0.09 and IC50 to be 6.1 mg.

Melamine (2,4,6-triamino-1,3,5 triazine) is widely used in paper, textiles, leather and other industries. It has been used in milk to increase the false protein content due to high nitrogen elements. DNA-Cu-NPs has been fabricated using ascorbic acid, DNA as template with fluorescence-based detection (Ga et al., 2020). Novel approach is to use AS1411 template for fluorescent copper nanomaterials. In presence of melamine, the fluorescence is quenched and can be easily detected with limit of detection from 50 to 120 μmol/L. This method of detection has been cost effective, highly sensitive with less complexity (Ga et al., 2020). These types of nanosensor systems help in food safety.

Ochratoxin A is mycotoxin that has high carcinogenic potential normally monitored by immunochromatographic assays. However, this method is expensive. To curb the cost, a chemosynthetic mimotope peptide has been developed to detect mycotoxin in 15 min with naked eye and the limit of detection to be 0.187 ng/mL (You et al., 2020). Mycotoxins can be considered as major contaminants leading to crop losses during storage. DNA aptamers are small nucleotides with fluorophore detected by FRET (Zhao et al., 2019). A novel graphene oxide based steganographic aptasensor has been fabricated for detection of zearalenone (ZEN) and ochratoxin (OTA) mycotoxins using capture probe Cy3 and Alexa fluor 488 aptamer. The detection limit of aptasensor was 1.79 ng/mL and 1.484 ng/mL for ZEN and OTA respectively (Wang et al., 2020). Mycotoxin zearalenone (ZEN) has been detected with an optical based nanobiosensor using a silicon dioxide layer using ZEN specific antibodies. ZEN specific antibodies are immobilised onto polyelectrolyte layer leading to refractive index changes upon binding to mycotoxin that confirms the presence of toxin with detection limit of 0.01 ng/mL (Nabok et al., 2021). Improvements in the performance of the electrochemical sensors using nanomaterials have been discussed (Gupta et al., 2021). Various electrochemical biosensors have been fabricated to detect food borne pathogens and toxins produced by *E. coli* and *Vibrio cholera* (Cesewski and Johnson, 2020).

Campylobacter jejuni contaminates the food that is responsible for major food outbreaks. DNA aptameric based nanobiosensors for detection of pathogens have been a significant method for food safety. High affinity single stranded DNA aptamers containing 59 nucleotides have been fabricated for detection of *Campylobacter jejuni* with the limit of detection of 10 CFU/mL. The accuracy of results has been confirmed by screening milk samples (Chen et al., 2020). Conventional methods of pathogen detection in food include time consuming cultural practices. *E. coli* has been considered as one of the indicators for food spoilage. Sol–gel derived ZnO nanoparticles and functionalised multiwalled carbon nanotubes have been designed for detection of *E. coli* using β-galactosidase (Meraat et al., 2020) with limit of detection of 10^1 CFU/mL in 15 min.

4.3. Nanobiosensors for packaged food

Nanobiosensors can be applied as coatings to the food packaging to detect possible leaking, elevated moisture and increased oxygen content which leads to the microbial growth. Packaging of food products ensures the quality and safety of food. Food packaging increases the shelf life of the food items by avoiding unfavourable factors such as pathogens, moisture and oxygen. Novel nanobiosensors have been developed to employ the concept of intelligent/smart nanobiosensors (Caon et al., 2017). Therefore, several radio frequency identification sensors (RFID) have been fabricated. The information regarding the quality of packages can be tracked from the company's website (Caon et al., 2017). Evaluation of food packaging technologies ensure the safety of food, robust monitoring and improved shelf life to meet demands from consumers (Sousa-Gallagher et al., 2016). Moreover, some nanomaterials provide protection of food from spoilage and moisture. Titanium dioxide being safer and nontoxic material can be used in food packaging (Dudefoi et al., 2018). Cellulose nanofibres are another cost-effective food packaging with least harmful effect on environment (Khalil et al., 2016). The next generation of food packaging involves intelligent robotic technologies. Intelligent packaging detects, senses and records changes in food products to ensure food quality (Vanderroost et al., 2014). Smart packaging involves monitoring of food conditions. Detection is associated with change in internal/external parameters along with feedback to customers (Primozic et al., 2021).

Currently, available intelligent packaging involves use of tags, labels, dots, inks that function in assurance of safety and food qualities (Ghaani et al., 2016). These labels monitor food conditions and give warnings to consumers related to freshness (Otles and Sahyar, 2016). Major challenge in developing robotic technology is cost. As food packaging in these cases accounts for 50% of the whole cost as compared to the fixed limit of 10% total cost.

4.4. Assurance of fruit quality

The quality of fruit products such as biochemical composition, maturity and ripening needs to be assured by the food industry before they are sold to the end customers (Rana et al., 2010). It is well known that fruits produce various organic acids at different amounts during their growth, maturation and shelf life. Thus, several successful biosensors have been developed to monitor the changes in organic compounds. Nanobiosensor has been fabricated using glucose oxidase to detect the formation of volatile compounds. Other factors include malic acid, fructose, benzoic acids and phenolics can be sensed to check the quality of fruits and their shelf life (Sharma et al., 2020; Pelle and Compagnone, 2018). One such nanobiosensor has been constructed for a new startup company named Strella Biotechnology by two researchers. This biosensor is based upon detection of ripened fruit by detecting ethylene (Brockmeier, 2019).

Table 3
List of patents for nanobiosensors in agri-food industries. Reported list of patents demonstrate the easy commercialisation of these novel diagnostic techniques for ensuring sustainability of agriculture and food industry.

Sr. No.	Patent number and date	Nanomaterial and biological component	Applications	Reference
1.	CN110018303A,2019	Fluorescence CdSe and Antibody against Salmonella	Quantitative estimation of pathogens	Chen et al. (2019)
2.	CN20191030172 A, 2019	Microfluidic chip and secondary antibody	Detection of pesticide Dithiocarbamate	Wang et al. (2019a,b)
3	KR1020200016780 A, 2020	Chitosan and enzyme of *Trichoderma harzianum*	Synthesis of chitosan nanomaterial	Wang et al. (2020)
4	US8951375 B2, 2008	Diatomaceous earth and Gold titanium oxide	Concentration methods of rapid detection of viable cells	Manjiri et al. (2008)
5.	CN110632302A, 2019	Gold nanoparticles with antibody against Salmonella.	Detectio of Salmonella and E. coli.	Zheng et al. (2020)
6.	CN 1020223147B, 2010	Aptamer and Magnetic nanoparticles	Detection of ochratoxinA	Wang et al. (2010)
7.	CN102628802A,2012	Aptamer and Metal nanoparticles	Detection and characterisation of Biotoxin	Wang et al. (2010)
8.	CN104634754B, 2015	Aptamer with magnetic nanoparticles	Detection of Terramycin	Tang et al. (2015)
9.	CN107238699A, 2017	Gold nanoparticles with peroxidase enzyme	Detection of Kanamycin	Nandi et al. (2017)
10.	CN107340245A, 2017	Aptamers	Detection of terramycin and oxytetracycline	Tour. (2017)
11.	US20200018764A1, 2020	Aptamer with signalling polynucleotide	Detection of food allergens	Geffen (2019)
12.	US20190295491A1, 2014		Nutritional and organoleptic analysis of food	Eugenio (2013)
13	WO202001458A1, 2019	Extraction methods for polynucleotides	Detection of microorganisms in rhizosphere	Bunkers et al. (2019)
14.	US20190331633A1, 2019	DNA and metallic nanoparticles	Detection of Plant pest causing rust	Li et al. (2019)
15.	CN110596218A, 2019	AchE and chitosan with silver nanoparticles	Detection of organophosphorus residues	Meiying et al. (2019)
16.	CN110632142A, 2019	Gold Palladium graphene quantum dots	Detection of organophosphorus and acetamiprid	He et al. (2020)

5. Patents on nanobiosensors

Various patents have been granted related to nanobiosensors and related innovative technologies depending on their significance in agri-food route (Table 3).

Magnetic material based nanobiosensors have been used commonly for detection of bacterial contaminants. The quick method of detection is based upon separation of magnetic nanoparticles associated with bacteria and thus increasing viscosity followed by centrifugation. On employing this nanobiosensor, the time of detection has been reduced from 5 days to few hours. Limit of detection in 105 colony forming unit within 30 min. The nanobiosensor has been fabricated by using microsized plastic magnetic particles with *Salmonella* antibody layer. Upon UV ray irradiation, food pathogenic bacteria separated and concentrated with nanobiosensor will fluoresce. The concentration of bacteria can be determined by the amount of fluorescence. So, this nanobiosensor can help in quantitative estimation of pathogens. Fluorescent nanoparticles have been coated with cadmium and selenium on inside and zinc sulphide on outside to enhance the optical properties (Myeong-Hyun et al., 2020).

Another patent has been granted to Chinese workers for antibody affinity-based detection. The sensitivity of such nanobiosensors is high due to highly specific immunogenic response that can be generated by binding of primary antibody with secondary antibody in presence of target molecule (Chen et al., 2019). A patent has been granted to tyrosinase based optical nanobiosensor for detection of pesticide dithiocarbamate. The low cost involved and ease in detection has been claimed. As the change in optical properties can be detected with smart phone carrying camera function, so this application prospect needs to be expanded (Wang et al., 2019a,b). Chitosan is an important base material for synthesis of nanoparticles. Fungal enzyme of *Trichoderma harzianum* has been used for synthesising smaller particles that is regarded as enhanced characteristic. These nanoparticles possessed good antioxidant activity with antibacterial property. Moreover, in vitro cell activity confirmed the suitability of the cost-effective chitosan nanomaterial (Myeong-Hyun et al., 2020).

Food borne pathogens such as *E. coli*. and *Salmonella* are primarily responsible for food poisoning. A patent has been granted for development of concentrating method of microorganism onto support such as diatomaceous earth coupled with gold and titanium oxide that is capable of collecting viable forms. This concentrating agent can be employed for variety of microorganisms and helped in capturing 70%–80% microorganisms within 30 min (Manjiri et al., 2008). Another patent has been granted based upon developing antibody specific for *E. coli* and *Salmonella* combining it with gold nanoparticles with single stranded DNA molecule. The samples for detection have been characterised by using Raman spectroscopy. With implication of such nanobiosensor detection of food borne pathogens can be achieved in less time duration with more accuracy (Jinkai et al., 2019). Amongst all food borne outbreaks, Salmonellosis caused by *Salmonella typhimurium* and all other serotypes is very common and threat to food industries. Recently, rapid and timely detection of *Salmonella* have been done using nanobiosensors (Shen et al., 2021).

Detection of toxins in food plays important role in ensuring the food safety. Method for detection of ochratoxin A by magnetic separation of adapter functionalised magnetic nanomaterial has been assigned a patent (Wang et al., 2010). Biotoxins is collective term to describe various types of toxins such as botulin, ochratoxin that can cause serious health problems such as cancer, neural paralysis and hepatotoxicity. These toxins can contaminate the food from storage, processing and packaging of food. In this invention, patent has been granted for fabrication of chip for detection of biotoxin. Here aptamers have been used as molecular probes that can competitively bind with biotoxins and modified by metal nanoparticles. These chips can detect various toxins in food with high sensitivity and quick response (Wang et al., 2010).

Antibiotic given to poultry, pig and other animals can be harmful for human beings and environment. Terramycin is one such antibiotic and method of its residue detection has been patented. In this method, probes have been prepared using aptamer of magnetic nanomaterial. Its limit of detection is 0.88 ng/mL with less fabrication and testing cost (Lu et al., 2015). Various other patents have been granted for detection of kanamycin using peroxidase enzyme combined to gold nanoparticles with aptamers which can be detected by magnetic isolation and produces colorimetric determination at 450 nm (Nandi et al., 2017). Likewise, colorimetric method for detection of terramycin and oxytetracycline has been granted patent (Luan et al., 2017).

Millions of people especially children are prone to food allergies. Most of the conventional approaches are expensive, time consuming and less sensitive for the detection of food allergens. A patent has been granted for aptamer containing polynucleotide signals-based detection of food allergens (Geffen, 2019).

Nutritional substances are very important to be identified and displayed as nutritional information has been critical criteria for food and beverage industry with rising concern about health. The patent has been granted providing information of all methods enabling and tracking changes in nutritional and organoleptic properties (Minvielle, 2013).

Microbiome/Rhizosphere of plants play important role in overall crop health. These beneficial microbes can enhance the absorption of nutrients from soil and increases the productivity. However, the pathogenic organisms can inhibit the plants. Thus, extraction and analysis of polynucleotides is important. Conventional methods involved the major problems of coextraction of unwanted components with more dilution which lead to polynucleotide below detection limit. A method for extract preparation has been patented that can result in better analysis of the polynucleotides (Bunkers et al., 2019).

Fungal pathogens such as *Fusarium* and *Sclerotinia* cause the rust diseases in plants. Nanobiosensor have been developed for detection of impedance in DNA probes for fungal pathogens (Li et al., 2019). Pesticide residues is another contaminant present in the soil. These pesticides can mix in food chains and cause problems in nerve conduction by effecting cholinesterase enzyme and leads to a metabolic disorder dyskinesia (Borji et al., 2020). A new method has been developed and granted patent using biological enzyme acetylcholinesterase immobilised on chitosan and silver adopted nanoparticles to detect organophosphorus pesticide residues with detection limit of 10–13 mol/L (Wang et al., 2019a,b). Enzyme based nanobiosensors using acetylcholinesterase along with various metal oxides have been developed (Alex and Mukherjee, 2021).

Similarly, another patent has been granted for developing electrochemical biosensor using gold palladium graphene quantum dot composite material in detection of chlorpyrifos, acetamiprid causal agent of so many human diseases and environmental pollution. This has resulted in extremely sensitive nanosensor with limit of detection to be 0.37 fM for acetamiprid (Zaijun et al., 2019). Pesticides such as acetamiprid that acts on synaptic site of insect nervous system are used for pest control during storage conditions (Liu et al., 2019; Madianos et al., 2017). Novel strategy for detecting acetamiprid using nanobiosensors have been explored as promising alternatives (Hassani et al., 2017; Verdian, 2018). A novel nanobiosensor comprising of aptameric DNA three-way junctions containing three single stranded DNA with G-quadruplex sequences at each end using graphene oxide for detection of acetamiprid (Zhao et al., 2021). This nanobiosensor is highly sensitive with limit of detection 5.73 nM. Moreover, this is the first report of nanobiosensor using three-way junction assembled for detection of pesticides. This nanobiosensor has very less noise on account of fluorescence quenching of graphene oxide and possess enormous potential to be used in agriculture and food industry.

Thus, the applications of reported patents clearly demonstrate the outstanding developments of nanobiosensors in the agri-food industry.

6. Challenges in nanobiosensors applications in agricultural and food industries

Although nanobiosensor can be a promising tool in the agricultural and food applications to ensure the viability and sustainability of these industries, there are still many challenges. For example, the application of nanomaterials is associated with concerns, particularly toxicity and ecotoxicity due to their unique nature (size, structure, high surface-to-volume ratio, and composition etc.). For this purpose, their impact on the environment should be assessed accurately in terms of size, dose, accumulation properties, immune response and retention time (Prasad et al., 2017). Another challenge to overcome is to fabricate miniaturised form to resolve portability aspects. For example, if the nanobiosensors can be successfully associated within information technology, the agricultural and food industries in the remote areas will be benefited in terms of the lowered cost, improved productivity, better understanding of outbreaks of diseases before their onset and better utilisation of natural resources such as soil, water and climatic conditions. Meanwhile, the cost involved in the fabrication of nanobiosensor still needs to be lowered. For this reason, alternative inexpensive biological components such as enzymes/cells, novel matrices for stabilisation/immobilisation of nanomaterials including chitosan can be used to improve overall stability and reusability of the nanobiosensor (Alvarado et al., 2019).

It is also challenging to transform nanobiosensors from a prototype to a commercial product. This is because the trials at field-scale are required to assess and evaluate the performance of nanobiosensors in real applications (Kaushal and Wani, 2017) and the awareness of nanobiosensors at the end users is quite important, too. Nanobiosensors need to follow all strict food regulations by food industries. He et al. (2020) suggested that most contemporary food manufacturers are reluctant to disclose their use of nanobiosensors to compete with their peers due to their concern of negative perception by customers on nanobiosensors. This behaviour may lead to the conflicts between the consumer and manufacturer.

7. Conclusion and future trends

Application of nanobiosensors in the contemporary agri-food industries is expanding to improve productivity by utilising natural resources more efficiently, which contributes to the sustainability of both agricultural and food sectors. Nanobiosensors can be applied starting from agri-food route, soil assessment, natural resources, evaluation of moisture, pH of soil, disease management, detection of pathogenic organisms, detection of chemicals and adulterants unsafe for humans to final commercialisation stage. There are few industries such as Roche, Nippon and IBM etc dealing with fabrication of nanobiosensors due to a wide spectrum of applications. Very few reports are available for commercialised nanobiosensors in agri-food industries. Although there are reports on commercial nanobiosensors in medical diagnostics and applications. High cost involved in fabrication, automation trials, evaluation of results and validation of field trials that prompts the miniaturisation of prototypes into industry for production is still a major challenge. Moreover, there is no market to offset and bear all these expenses. That may be the reason for less commercial nanobiosensors available. However, deriving the novel nanomaterial from waste biomass can provide a cost-effective alternative. Versatility of the nanobiosensor is another aspect that needs to be addressed further. Developing an array of nanomaterials for biosensing a number of materials based upon bioassays can lead to more commercialisation of nanobiosensors with portable sizes.

In the future, nanobiosensor devices can be potentially associated with the GPS system to contribute to precision farming and smart agriculture. As a result, farmers will be able to make better decisions on irrigation, fertilisation, pest control and harvesting with lower natural resources requirements. The present article may be concluded with the discussion that customised nanobiosensors pertaining to requirement with high specificity and sensitivity will be realistic in near future.

CRediT authorship contribution statement

Meenu Thakur: Writing – original draft. **Bo Wang:** Writing – review & editing. **Madan L. Verma:** Writing – original draft, Writing – review & editing, Developed the theoretical framework.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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