NANOCOMPOSITE BIOSENSORS FOR POINT-OF-CARE— EVALUATION OF FOOD QUALITY AND SAFETY

Anisha A. D'Souza, Durga Kumari, Rinti Banerjee
Nanomedicine Lab, Department of Biosciences and Bioengineering, Indian Institute of Technology, Mumbai, India

1   Introduction

Increased outbreaks in foodborne illness and the need to meet the demands of growing populations have been the driving forces for ensuring that food production undergoes quality control for evaluation of its fitness for human consumption (Sekhon, 2014). Food safety is crucial at every step right from its production to its preservation, transportation, and consumption. Consumers expect optimal quality, good stability, and a safe food product at a reasonable price. Monetary and legal aspects related to food products as a consequence of food contamination are of grievous concern to food producers accompanied with loss of consumer confidence (Odumeru, 2002). With these concerns, food safety and nutritional quality have always been a priority issue for producers, food safety regulators, the food industry, and consumers (Karlsson, 2004). Foodborne illness could also be as serious as botulism, listeriosis, or hemolytic uremia syndrome, which often need hospitalization. Hence, an accurate and quick monitoring of food quality should be feasible during various stages of food production until consumption.

Conventional analytical methods mandate high numbers of pathogens or analytes for visual or identifiable changes in food. Low levels of analytes in food generate low signals with great variations, which are difficult to detect with confidence (Rodríguez-Lorenzo et al., 2012). Moreover, many analytical techniques are destructive and affect the seal of the packaged food (Duncan, 2011). Until recently, most of the biosensors developed
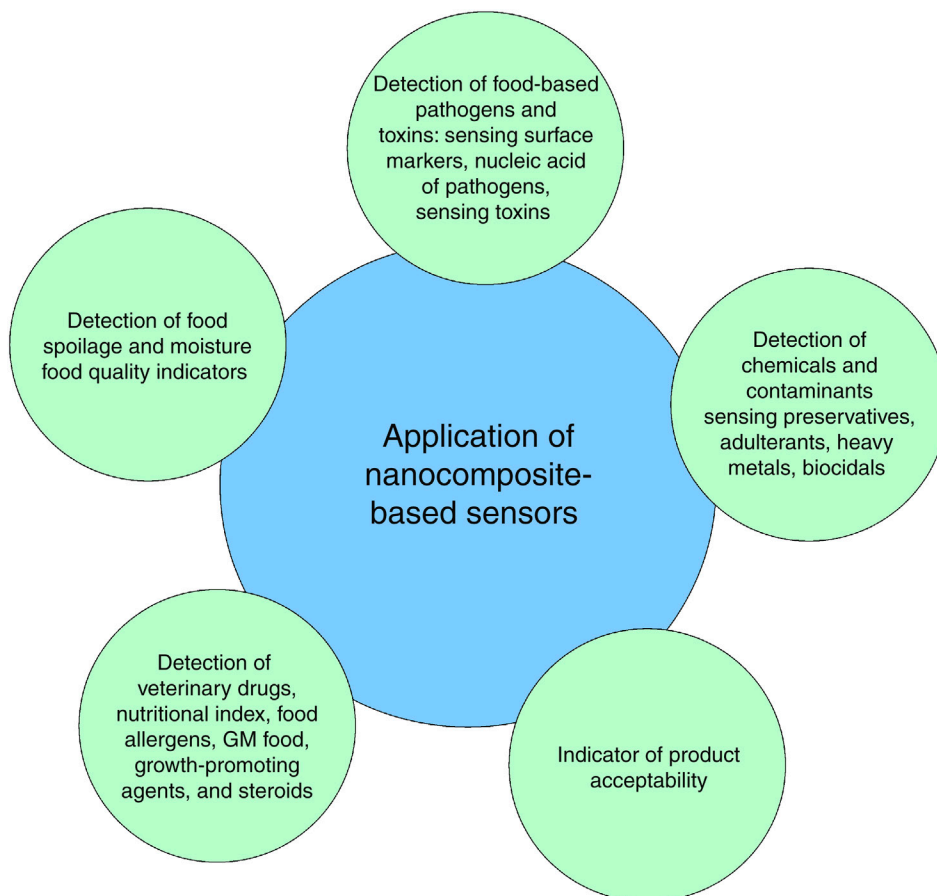
Figure 15.1. Nanocomposite based biosensors in food quality and safety.

were marketed for medical applications. Moreover, food matrices offer many limitations due to their opacity, coloring matter, light scattering and complexity of food materials. Advances in the area of analytical methods and scientific tools, with better detection methods in the complex matrix of foods, thus dictate the need for development of advanced biosensors for the food industry.

Nanocomposite-based biosensors provide new solutions to tackle critical analytical evaluation and detection problems of contaminants and achieving quality and safety in the food industry. The unique traits of nanoscale composites with improved stability make them outstanding for sensor applications (Fig. 15.1). Their use has enabled improved sensitivity and portability with unparalleled performance and real-time sensing in complex matrices. The current chapter features the various nanocomposites

employed in improving the conventional analytical and sensing applications in the food industry. Additionally, monitoring of food freshness, pathogen contamination and toxins in food products, after being dispatched until they are consumed requires point-of-care sensing technology. The chapter describes specific demands of nanocomposite-based nanosensors in addressing crucial segments related to food safety and quality, such as determining contamination, pesticide residues, antibiotics, shelf life and organoleptic assessment at point of care. The chapter also discusses the existing and future prospects of nanotechnology-based biosensors along with their commercial potential.

2 Biosensors and the Food Industry

As per the International Union of Pure and Applied Chemistry, biosensors are devices that contain an amalgamation of receptors with transducers for selective quantification using incorporated biological recognition elements (Thévenot et al., 2001). The receptor of a biosensor recognizes and interacts with the analyte. Receptors could be enzymes, antigens (Ag), nucleic acids, or organelles performing an affinity, biochemical, or catalytic reaction. Binding or catalysis between receptors and substrate transforms the physical, chemical, or biologic information to some form of energy, such as, electrochemical, optic, fluorescence, mass, or calorimetric signals, which is measured by the transducer. The transducer thus provides quantifiable physicochemical signals proportional to the analyte concentration (Thakur and Ragavan, 2013).

Biosensors are widely used to determine contamination, raw material and product composition. They also keep tab on quality check. Besides government's mandatory regulations, quality check also encompasses nutritive value; degree of food spoilage, especially of meat and fish; degradation during storage; processing, distribution, and presentation fit for human consumption; peak freshness, with minimized opportunity for foodborne diseases; and health hazards on food consumption. Monitoring organoleptic characteristics, such as, smell, odor, and taste of food is also an important parameter for determining food quality. Rapid, nondestructive detection of foodborne pathogens, pesticide residues and allergens with high analytical sensitivity are the major needs of the food industry (Murugaboopathi et al., 2013). Additionally, on-site monitoring of fermentation, antibiotic residues, and toxins in food is also required in the food industry.

Noninvasive sensing technology at point-of-care settings may be beneficial for food testing, especially if the analytes can
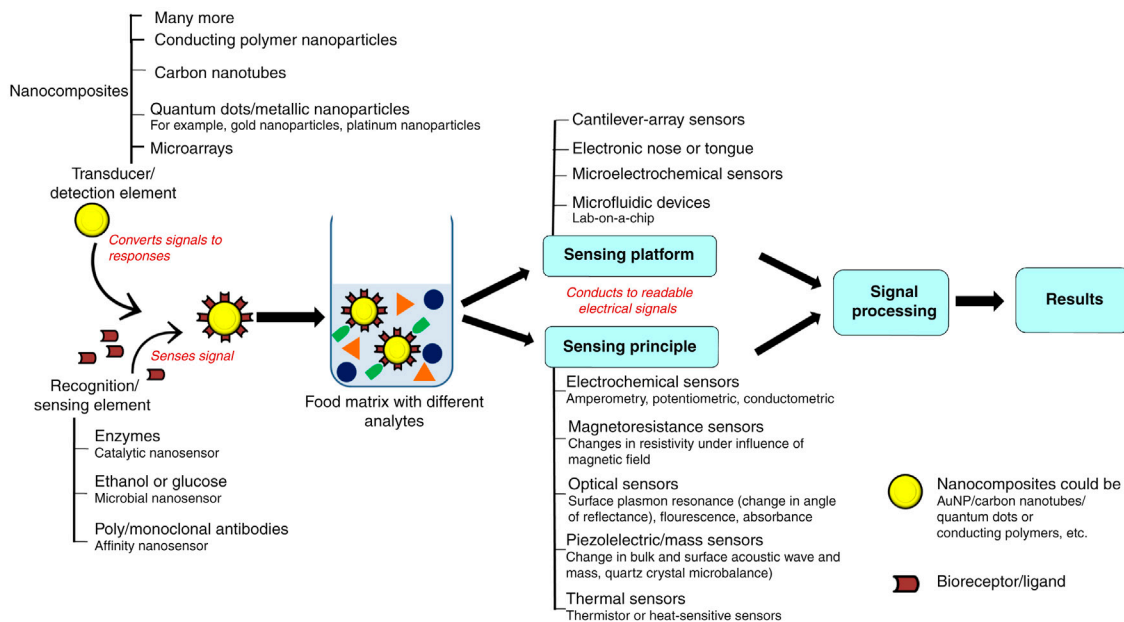
Figure 15.2. Role of nanotechnology in sensors for food safety and quality assessment.

be determined just by visual observation of the product. The demand for quick and specific biosensors for analysis of food has thus been continuously rising and expanding to address the different aspects of food quality and safety. Friendly applicability and simplified communication with end users are the ultimate striving goals for assuring quality of food products.

3   Nanocomposite-Based Biosensors

Nanotechnology is "the understanding and control of matter that involves manipulation of structures at dimensions of 1–100 nm" (Sargent, 2014). Application of nanotechnology to sensors or biosensors in the food industry is known as "nanosensors" or "nanobiosensors," respectively. Nanosensors are relatively a new concept in the food industry compared to their application in pharmaceuticals. Nanocomposites are utilized in several ways to improve the efficiency of nanosensors. They essentially consist of nanoparticles (NPs) attached to any of the various recognition labels followed by detection through any of the sensing approaches illustrated in Fig. 15.2. Nanotechnology in sensing, permits miniaturization of sensors which facilitates their integration with normal food production and packaging machinery and equipment, or can

be used offline as point-of-care devices (Leonard et al., 2003). The demand for analyte samples and reagents used in nanosensors is less than that of conventional methods of detection. Additionally, the time factor involved for detection is significantly reduced from hours to minutes compared to many traditional laboratory analytical techniques.

Nanomaterials differ in properties from those of the bulk macroscopic material due to their existence and interaction at the atomic levels. The small size of nanomaterials (1–100 nm) results in large surface areas with high surface reactivity, high electric conductivity, enhanced magnetic properties and improved quantum confinement effects, such as, luminescence and catalytic properties, making them very sensitive (Kaittanis et al., 2010) with high analyte-capturing efficiencies (Duncan, 2011). The slightest modification of the nanostructures with respect to their size, self-assembly, surface composition, and shape alters and tunes their electronic, conductive, fluorescence, light-scattering, binding properties and the absorption-emission spectra. They can also permit engineering with different molecules and combinations of individual bioaffinity agents and act as transducers to enable ultrasensitive detection, as well as, multiplex sensing assays for different pathogens and protein-based toxins (Tallury et al., 2010; Xu and Ying, 2011). For instance, in one study, combinations of metallic platinum nanocomposites and single-walled carbon nanotubes coated on glassy carbon provided enhanced sensitivity for detection of hydrogen peroxide and glucose over individual nanocomposites by voltammetry within 3 s. The presence of nanocomposites ensured that the electric contact of the glass electrode and the biosensor loaded with glucose oxidase enzyme was more sensitive than that of an unmodified glass electrode loaded with the same enzyme (Hrapovic et al., 2004).

The unique properties of nanomaterials can thus be easily exploited for improving sensitivity, robustness, and reproducibility of biosensors, diagnosing within a shorter span of time, and at the same time being relatively economical (Nath et al., 2008). Nanoproperties change before and after binding with analytes. A simple example would be illumination with different-colored fluorescence on interaction with different pathogens. They permit real-time and online qualitative and semiquantitative detection. They can be also called "naked eye chemosensors." Such online sensors provide greater control over product properties during manufacturing, thus improving product quality and cost reduction (Ravindranath et al., 2009). Incorporation of nanoparticles (NPs) into composites also permits intimate contact with analytes like pathogens, as NPs often exhibit size similar to biologic species, such as, bacilli and viruses.

Gold nanoparticles (AuNPs) exhibit length-dependent absorption properties; permitting simultaneous detection of organisms. Hybrid nanocomposites of iron oxide–gold nanorods and iron oxide nanodumbbells have tunable optic and magnetic properties. Iron oxide–gold nanorods upon binding with pathogens exhibit different aspect ratios and thus differ in plasmon properties and also facilitate magnetic separation. This functionality was explored for multiplex optic detection (Wang and Irudayaraj, 2010). Nanowires conjugated to fluorescent antibodies (Ab) can detect pathogenic microorganisms. For instance, if the food contains traces of *Salmonella*, *Salmonella* Abs conjugated to fluorescent antibodies are coated on the nanowire. The Ab-coated nanowire upon interaction with *Salmonella* would alter the fluorescence of the probes, making them visible (Dingman, 2008). The nanocomposite-based nanosensors thus permit visual identification of pathogens at point-of-care without significant lag time, and serve as a simple technique for consumers to know the quality and safety of food products.

Coupling of metallic NPs to affinity ligands can lead to sensing of genetic strands, bacteria, or toxins using any of the sensing principles based on change in fluorescence, magnetic, Raman scattering, and electrochemical changes, as depicted in Fig. 15.2 (Alivisatos et al., 2005). The high sensitivity of nanosensors permits real-time detection and quantitation at molecular and single-cell levels (Tallury et al., 2010). Online real-time analysis has significantly reduced the time for pathogen detection. Earlier analytical techniques needed over 24 h for permitting sufficient growth of pathogens to be detected (Mahalik and Nambiar, 2010).

NPs exhibiting magnetic, fluorescence and conductive materials have been exploited for detection, imaging and tracking through various probes. For instance, quantum dots (QDs) permit labeling and visualization, replacing classical fluorophores. Metallic NPs are conducting in nature and thus wiring of the biologic unit facilitates a rapid transfer of electrons. Hence, electrodes are often modified with a monolayer of AuNPs conjugated to bioelements. In one study, glucose oxidase conjugated to silver/gold/platinum NPs electrodeposited on metal electrodes enhanced transfer of electrons between enzyme and electrode with improved stability (Zhu et al., 2007). The role of conducting polymer nanowires and semiconductors as nanomaterials in sensor applications has already been reviewed (Willner et al., 2007).

Application of nanotechnology in nanosensors is, however, not restricted only to recognition labels but could range from recognition element to transducer or running systems. Platforms technology of nanotechnology in microfluidics, microelectromechanical
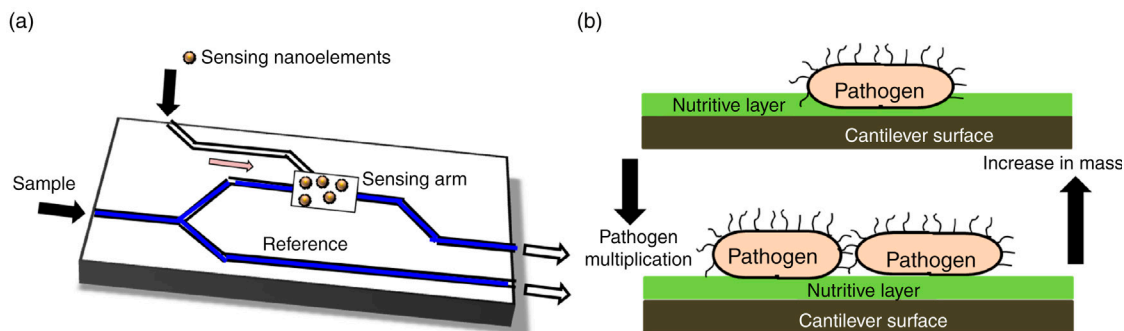
Figure 15.3. Schematic representative of (a) simplified microfluidic system (b) mass sensors used in nanocantilever. Increase in bacterial growth increases bacterial mass and depletes nutritive layer deflected by nanocantilever due to change in mass.

systems, cantilevers, and microarrays have further widened the realm of quality analysis (Sozer and Kokini, 2012) (Fig. 15.3).

Microfluidic systems based on silicon have been popular as laboratory-on-a-chip technology. They are multifunctional wherein sampling, separation, reaction, and detection can be performed on the same device. *Nanocantilever*-based sensors have been used to detect various molecular interactions, such as, Ag–Ab, enzyme–substrate–cofactor, chemical interactions, receptor–ligand and nucleic-acid hybridization (Hall, 2002; Kumar, 2007). Bio-Finger is a portable nanosensor consisting of nanocantilevers made of piezoresistive material for detection of pathogens, chemicals, and toxins in food based on ligand–receptor interactions. Any binding or interaction between an Ag and Ab induces mechanical stress on the nanocantilever, which is coated with antibodies, and changes the electric resistance of the material. Multiple such nanocantilevers can be arranged in an array to form a single chip. The total analytical time for detecting the analyte is 15–20 min. The cost of Bio-Finger is expected to be $10, cheaper than the existing diagnostic techniques. Arrays have an upper hand in obtaining sensitive and simultaneous detection of analytes. Reference sensors can also be incorporated into the array, minimizing the noise.

4   Application of Nanosensors in the Food Industry

4.1   Detection of Foodborne Pathogens and Toxins

Food contamination caused by pathogens (bacteria, fungi, protozoa, viruses, prions, and worms) and toxins remains a major concern globally. Conventional techniques for identification of

pathogens include microscopic examination, growth patterns of culture upon culturing in differential media, their biochemical tests, and immunoassays (Tallury et al., 2010).

These techniques are laborious, with lag times greater than 24 h for pathogen amplification. The process of sample preparation remains a determinant for specificity and sensitivity of many assays (Kaittanis et al., 2010). Lately, molecular diagnostics, such as, identification of DNA segments and proteins of the pathogen's genome and virulent strains using polymerase chain reaction (PCR), ligase chain reaction, and checkerboard hybridization have been employed (Tallury et al., 2010). However, these methods mandate the need of undamaged microbial DNA for detection. Identification of circulating Abs and specific cell-wall epitopes made of carbohydrate or proteins can also be achieved by immunoassays, phage typing, and flow cytometry; but are limited to homogeneous, purified, and simple matrix samples (Kaittanis et al., 2010).

4.1.1 Sensing the Surface Markers

RuBpy dye [Tris(2,2′-bipyridyl) dichlororuthenium (II) hexahydrate] labeled with Ab-conjugated silica fluorescent NPs (60 nm in diameter), which were conjugated to anti-*Escherichia coli* Ab, enabled single *E. coli* O157:H7 detection obtained from processed beef samples within 20 min. The fluorescent signal of the dye varies on the biorecognition of *E. coli*. Sensitivity of the method was similar to that of conventional plate counting but with a shorter readout time. The technique also permits high-throughput quantitation of 1–400 bacterial cells using microtiter plate reader (Zhao et al., 2004) (Fig. 15.4). Silicon/gold nanorod nanoarrays functionalized with anti-*Salmonella* Abs bearing organic-dye particles become visible in the presence of *Salmonella*. The high aspect ratio of silicon nanorods upon interaction of anti-*Salmonella* Abs with *Salmonella* Ags shows increased fluorescence intensity of dye molecules (Fu et al., 2008).

Electrostatic interactions of AuNPs functionalized with fluorescent π-conjugated anionic polymers like *p*-phenylene ethylene results in quenching of fluorescence. However, in cases of bacterial contamination, fluorescence emission increases due to displacement of the anionic polymer with the negative cell surface of bacteria, including *E. coli*, *Lactococcus lactis*, *Streptomyces coelicolor*, and *Bacillus subtilis*. Linear-discriminant analysis generates a characteristic signature plot specific for each microorganism. The method has been successful for detection of 1×10^9 CFU (ie, $OD_{600} = 1$) (Phillips et al., 2008). Different strains of norovirus, parvovirus, corona virus, adenovirus, simian rotovirus, herpes virus, and Sendai virus at a count of 100 particles in food and drinking water have been discriminated using AuNPs (Fan et al., 2010).
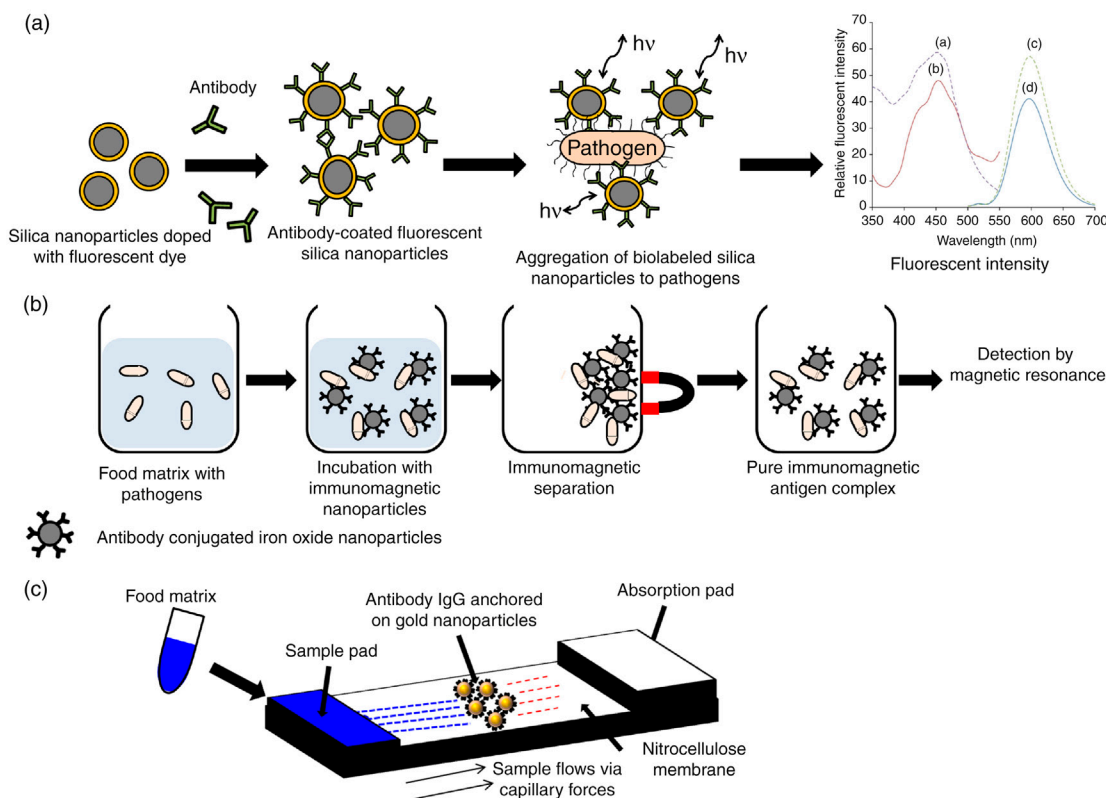
Figure 15.4. (a) *E. coli* Ab conjugated silica fluorescent NPs for detection of *E. coli* using fluorescence intensity; (b) quantitation and detection of pathogens using immunomagnetic NPs; (c) immunochromatographic separation of pathogens on nitrocellulose membrane

Surface-enhanced Raman scattering (SERS) based on nano-structured gold and silver nanorods as substrates, can detect and differentiate strains of bacillus species and simultaneously screen *E. coli*, *Listeria monocytogenes*, and *Salmonella typhimurium* within 10 s of collection time (He et al., 2008; Chu et al., 2008). Principal component analysis is used to analyze the Raman scatter and classify the data according to the presence of different species, strains, and Gram-types. Yet another advantage is the differentiation between viable and nonviable cells. Nonviable cells have significantly reduced SERS (Chu et al., 2008). Surface plasmon resonance (SPR) effect of AuNPs improved the performance and sensitivity 10-fold compared to conventional methods (Chen et al., 2004).

Interaction of magnetic NPs with pathogens undergoes spin–spin relaxation time (T_2) of adjacent water molecules (Chemla et al., 2000). Change in relaxation times (ΔT_2) can be detected by benchtop-magnetic relaxometer (20 MHz, 0.47 T) or

superconducting-quantum interference device (SQUID) or by magnetic resonance imaging (60 MHz, 1.5 T) (Zheng et al., 2009b). The higher the relaxivity of iron-oxide NPs, the higher is the sensitivity of detection. *Mycobacterium avium* spp. *paratuberculosis* (MAP) was quantified in whole milk using spherical iron-oxide NPs and dextran-coated iron oxide nanorods (R^2 300 M/m per s) within 5–30 min without any interference (Kaittanis et al., 2007; Nath et al., 2008). In the presence of MAP, conjugation of iron-oxide NPs changed the spin–spin ΔT_2 of water protons. Low bacterial concentration caused assembly of NPs on bacterial surfaces, and hence high ΔT_2 was observed. While at high bacterial concentrations, ΔT_2 decreased due to the dispersed state of the NPs. In the presence of a magnetic field, NPs acquire magnetization. On switching off of the magnetic field, free NPs relax rapidly by Brownian rotation and thus do not contribute to any signals. Abs bound to pathogens are immobilized and undergo Neel relaxation; that is, the oscillations vary in the presence of a target with slow decay of magnetic flux, dissipating magnetic flux detectable by SQUID, as opposed to, the change in Brownian motion observed in free NPs (Chemla et al., 2000). Magnetic NPs conjugated to Ab and immobilized with SQUID on amylar film detected *L. monocytogenes* above a count of 6×10^6 (Grossman et al., 2004). However, the requirement of high infrastructural costs limits the application of these magnetic NP-based sensors for the food industry.

Nanosensors commonly use immunoassays with Ab immobilized on NPs coupled with immunocapture for detection (Warriner et al., 2014). Immunomagnetic separation is performed to concentrate the analytes or pathogens above the signal-to-noise ratio. Antibodies specific to analyte or pathogen are conjugated to magnetic particles followed by separation with a magnet prior to detection (Fig. 15.4b). *L. monocytogenes* have been captured by immunomagnetic NPs during a 2 h time duration. The immunomagnetic NPs consisted of magnetic NPs (diameter of 30 nm) functionalized with *L. monocytogenes* Ab via biotin–streptavidin linkages. The separated complex was injected into a microfluidic chip and detected using an impedimetric immunosensor at 102 Hz. Resistance of complexes dispersed in mannitol solution decreased the impedance. The method was sensitive in simple matrices, such as, buffers with a sensitivity of 10^3 CFU/mL. The sensitivity decreased in matrices like milk, lettuce-rinse samples, and beef homogenates with a limit of detection of 10^4–10^5 CFU/mL within 3 h due to interference of high protein/fat content. The method exhibited high specificity in the presence of other foodborne bacteria like *E. coli*, *Staphylococcus aureus*, and *Salmonella tyhphimurium* (Kanayeva et al., 2012). AuNPs conjugated to secondary enzyme-labeled

L. monocytogenes Ab detected *L. monocytogenes* with high specificity over other enteric bacteria at 2 log CFU/g in wild-blueberry samples. The NPs were immobilized on screen-printed carbon electrodes for amperometric sensing (Davis et al., 2013).

Magnetic iron-oxide NPs conjugated to vancomycin quantified *S. aureus* using a magnetic resonance system. Vancomycin interacted with the peptidoglycan of the bacterial cell wall. The method could detect almost 10 bacteria present in 10 μL of sample within 15 min. The magnetic NPs form clusters upon identification of the analyte and the self-assembled cluster complexes decrease the nuclear spin of surrounding water protons (T_2). Detection of T_2 was possible by a handheld portable device consisting of a microcoil array for nuclear magnetic-resonance measurements, a microfluidic network for handling sample and mixing with NPs, and a permanent magnet to generate a polarizing magnetic field (Lee et al., 2008). The combination of gold-microelectrode array in a microfluidic device along with magnetic NPs conjugated with Ab helps in detection of pathogens, for example, *E. coli* in ground beef. The bacterial cells were concentrated by immunocapture by a factor of 10^4–10^5 in a volume of 400 pL; and the metabolism was detected by impedance. Detection time was comparatively reduced with bacilli in a dilute sample (Gomez-Sjoberg et al., 2005). *E. coli* could be detected with nanocantilever coated with agarose-nutritive media for bacilli. As the mass of the cantilever array increased, the resonance frequency changed. The cantilever could detect a mass of approximately 100 active *E. coli* cells within 1 h (Fig. 15.3b). Selectivity of the method could be improved by adding antibiotics to the nutritive media (Gfeller et al., 2005). Likewise, magnetic NPs conjugated to anti-H5N1 Ab aggregated in the presence of avian flu virus. High transition-temperature superconducting quantum interference senses the immunomagnetic reduction of the reagents and allows quantitation of H5N1 in wash-free samples (Yang et al., 2008). Diagnostic kits containing AuNPs have been studied for detecting influenza virus in poultry. These diagnostic kits have AuNPs conjugated with specific protein of the avian influenza virus (Emami et al., 2012). Literature has ample such examples for detection of pathogens (Table 15.1).

An immunochromatographic assay for rapid detection of *S. aureus* has been developed by Huang et al. (Huang, 2006; Huang et al., 2007). On a defined zone of nitrocellulose membrane, IgG antiprotein A (cell wall protein of *S. aureus*) conjugated to AuNPs was mobilized. Two precooked foods naturally contaminated with bacterium and 11 processed foods artificially spiked with *S. aureus* were allowed to flow past the IgG antiprotein by capillary action. A red color was seen for the specific reaction with antiprotein A at

Table 15.1 Nanosensors Used for Detection of Pathogens

Analyte	Nanomaterial	Detection Method	Detection Limits	References
Bacilli				
Campylobacter jejuni	Lectin immobilized on gold surface of quartz crystal electrode	QCM	Reusable, limit of detection 10^3 cells within 30 min	Safina et al. (2008)
E. coli O157:H7	Core-shell Cu/AuNPs with anti-*E. coli* Ab	Anodic-stripping voltammetry	Detection limit is 30 CFU/mL within a time span of 2 h	Zhang et al. (2009)
	Magnetic nanobeads	Impedance spectroscopy	45 log CFU/g in freshly ground beef, assay time 35 min	Varshney et al. (2005)
	Ab immobilized gold-coated on QCM	QCM with dissipation monitoring	Log–log linear working range 10^7–10^9 cells/mL	Poitras and Tufenkji (2009)
	Anti-*E.coli* Ab immobilized on PEG alkanethiol monolayers on SPR	Sandwich assay SPR immunosensor	Detection limit 10^6 CFU/mL, highly specific against *Salmonella enteritidis*	Subramanian et al. (2006)
	Sugar attached to iron-oxide NPs	Fluorescent staining	Can isolate up to 88% of *E. coli* within 45 min	El-Boubbou et al. (2007)
	Ab coated on iron-oxide NPs	Optic detection using FTIR/portable mid-IR	10^4–10^5 CFU/mL in 2% milk and spinach extract	Ravindranath et al. (2009)
S. aureus, *Vibrio parahaemolyticus*, and *S. typhimurium*	Multicolor upconversion NPs (rare-earth ions) coupled with aptamers attached to magnetic NPs	Magnetic NPs used for immuneseparation with aptamers followed by visible luminescence	25 CFU/mL for *S. aureus* 10 CFU/mL for *V. parahaemolyticus* 15 CFU/mL for *S. typhimurium*	Wu et al. (2014)
S. typhimurium and *S. aureus*	AuNPs labeled with Raman reporter molecules	Raman scattering	10^3 CFU/mL in spinach wash and peanut butter emulsion	Zhuyi et al. (2011)

Table 15.1 Nanosensors Used for Detection of Pathogens (*cont.*)

Analyte	Nanomaterial	Detection Method	Detection Limits	References
S. typhimurium	Protein G-coated 11-mercaptoundeca-noic acid monolayer on gold surface	SPR	10^2–10^9 CFU/mL	Oh et al. (2004)
S. typhimurium, Shigella flexneri, and *E. coli* O157:H7	Combination of magnetic NPs and Ab-conjugated semiconductor QD	Magnetic NPs immobilized with Ab and quantified by fluorescence	10^{-3} CFU/mL within 2 h in food matrix protein in high concentration decreased sensitivity of the method	Zhao et al. (2009)
Salmonella	Anti-*Salmonella* Ab immobilized to QD	Fluorescence at 415 nm UV	4×10^3 CFU/mL in food extracts	Kim et al. (2013)
S. aureus	AuNPs immobilized with anti-*S. aureus* Ab	Magnetic beads enhance capture of *S. aureus* from milk matrix florescence of gold quantified	Assay time 40 min, low sensitivity with detection limit of 5 log CFU/mL	Sung et al. (2013)
Viruses				
Cauliflower mosaic virus	Lead sulfide NPs linked to cauliflower mosaic virus 35S oligonucleotide	Sensitive differential pulse anodic stripping voltammetric	Detection limit was 4.38×10^{-12} M/L	Sun et al. (2008)
Tomato ring-spot virus and grapevine fan leaf virus	Mesoporous silicon	Change in electric parameters after adsorption	Effective virus size for detection was 50 nm	Vashpanov et al. (2008)
Spores				
Bacillus anthracis spores	Polyaniline-coated magnetic NPs (100 nm)	Detection mechanism depend on capillary flow of captured spores	Limit of detection 4.2×10^2 spores/mL within 16 min	Pal and Alocilja (2009)
Bacillus thuringiensis spores	60-base aptamer conjugated to zinc-sulfide capped CdSe QD	Detects at 655 nm with no photo bleaching of QDs	Semiquantitative, specific and detects 1000 CFU/mL	Ikanovic et al. (2007)

<25 CFU/g. The same technique could identify 28 different strains of *S. aureus* and 23 non-*S. aureus* strains (Fig. 15.4c).

NanoBioluminescence Detection Spray developed by AgroMicron contains a luminescent protein engineered to detect *Salmonella* and *E. coli*. The spray is directly applied to food or beverage and the proteins react with the pathogens, producing a visual glow.

4.1.2   Sensing the Nucleic Acids of Pathogens

AuNPs cause the free electrons in the conduction band to form plasmonic bands. Any minor change in the dielectric constant locally either by adsorption or by aggregation shifts the plasmonic bands. Interaction between nucleic acid and AuNPs causes a shift in the peak of SPR (Sun and Xia, 2002). For detection of anthrax, AuNPs are used in probes. Hybridization between the target gene and the AuNP-based probes alters the dielectric constant and hence diffraction of light. This method is simple, specific, and sensitive with a color-selective nature and was found to detect anthrax lethal factor as low as 40 fM concentration (Bailey et al., 2003).

Methicillin-resistant strains of *S. aureus* possess the mecA gene, which can be detected using DNA-modified AuNPs and does not require target or signal amplification (Storhoff et al., 2004). AuNPs capped with oligonucleotideprobes (alkanethiol-31 nucleotide probes) have been studied in detecting the invA gene of *Salmonella*. On amplification of the target gene by PCR, high sensitivity was observed in comparison with agarose gel electrophoresis. Detection limit of the probe was 21.78 ng/μL (Majdinasab et al., 2012). AuNPs assembled via 2-aminoethanethiol on the surface of gold chip were immobilized with gold-binding polypeptides (GBP)–protein A–human IgG conjugated to anti-*Salmonella* Ab. The surface modification intensified the binding signal intensity threefold and caused a 10-fold increase in sensitivity in comparison with the bare chip (Ko et al., 2009). The detection techniques of nucleic acids and those involving SPR techniques currently are limited to only clean, isolated samples, and evaluation of the same in mixed matrices of food analyte is warranted.

4.1.3   Sensing Toxins

Toxins disrupt the phospholipid bilayer of host cell plasma membranes by generating pores within the layer. Fungal toxins (mycotoxins), cyanobacterial toxins in freshwater, and marine toxins in shellfish are retained in food samples even after the death of the pathogen (Kayal and Charbit, 2006). Regulatory bodies have set maximum permitted levels for mycotoxins in food products

(European Commission Regulation, 2006). Detecting low levels of mycotoxins is a challenging issue in complex food matrices (Berthiller et al., 2014).

AuNPs coated with thiolated lactose derivatives mimic the distal portion of GM1 ganglioside, an extracellular matrix of intestinal epithelial cells, and conjugates with cholera toxins. Interaction of toxin and NPs occurs within 10 min with a red shift of the plasmonic band and allows a detection limit of 54 nM (Schofield et al., 2007). Similarly, globotriose-coated AuNPs resemble the globotriaosylceramide present on renal epithelia and intestinal microvilli. The B subunit of Shiga-like toxin interacts with this bio-artificial substrate and permits visual detection of the interaction (Chien et al., 2008).

In another study, multiplexed sandwich fluoroimmunoassays have been used for simultaneous examination of four toxins—cholera, ricin, Staphylococcal enterotoxin B, and Shiga-like toxin 1 using cadmium–selenide–zinc sulfide (CdSe/ZnS QDs) at four different wavelengths after binding to their specific Ab (Goldman et al., 2003). Staphylococcal enterotoxin B isolated from food samples by immunomagnetic separation using magnetic NPs coated with anti-Staphylococcal enterotoxin Ab could be quantified by fluorescence nanotransduction (Branen et al., 2007). Fluorescent quantum dots (QDs) have also quantitated Staphylococcal enterotoxin B, ricin, cholera, and Shiga-like toxin. Europium quantum dots depicted sensitivity of 10 pg/mL, 100 times more than conventional enzyme-linked immunosorbent assays (Tang et al., 2009b). Ab-labeled luminescent QDs have also been studied for detecting botulinium toxin serotype A with picomolar sensitivity (Warner et al., 2009).

Staphylococcal enterotoxin B reacts with polyclonal Ab-coated AuNPs and then with fixed polyclonal Ab on porous nitrocellulose membranes placed in a lateral-flow assay device. Toxin–Ab reaction reproducibly led to the formation of a red line at the detection zone within 5 min with increased sensitivity up to 10 pg/mL on silver enhancement (Rong-Hwa et al., 2010). Likewise, AuNPs conjugated to IgG-rabbit anti-Staphylococcal enterotoxin B immobilized on a polycarbonate surface, enabled detection of Staphylococcal enterotoxin B. The food analytes were mainly tomatoes, baby foods, and mushrooms spiked with enterotoxin, centrifuged, and passed through a cation exchanger, carboxymethyl cellulose analytical column to remove the interfering food materials. After incubation of these eluted samples with the membrane for 45 min, the membrane was exposed to HRP-conjugated anti-Staphylococcal enterotoxin B IgG and detected by chemiluminescence. Detection limit was 0.01 ng/mL (Yang et al., 2009).

Aflatoxin (toxins of Aspergillus) detection has been studied with AuNPs bearing aflatoxin Ab up to levels of 0.5 ng/mL in grains within 15 min. Immobilization of these NPs on immunochromatography strips facilitated portability with performance comparable to that of high-pressure liquid chromatography (HPLC) (Shim et al., 2007). Toxins in milk interact with aflatoxin M1 Ab anchored on iron-oxide NPs, isolating the toxins and allowing quantification by enzyme-linked immunosorbent assay (Radoi et al., 2008). Aflatoxin B1 in artificially contaminated milk up to concentrations of 0.01 ng/mL could be detected using piezoelectric immunosensor based on AuNPs (Jin et al., 2009). Nanoiron-oxide NPs core coated with AuNPs as shell, detected aflatoxin B2 in nuts when used as labels in a lateral-flow immunodipstick with similar results as obtained by HPLC but with a shorter readout time of 15 min. Samples for analysis were prepared by extraction of ground peanuts, hazelnuts, pistachios, and almonds with an admixture of methanol and water followed by filtration (Tang et al., 2009a). Immunomagnetic NPs conjugated to polydopamine-extracted aflatoxin from liquid food samples with 59% recovery in case of aflatoxin AF and 89% of aflatoxin B1 in red wine. It thus helps in concentrating the analyte, which can then be analyzed (McCullum et al., 2014).

Antimicrocystin-LR-coated single-walled carbon nanotubes bind to microcystin-LR (toxin released by cyanobacteria) in drinking water up to levels of 0.6 nM. The method is an improvement over the sampling time involved in the traditional method of quantitation by enzyme-linked immunosorbent assay (Wang et al., 2009a).

Recently, antideoxynivalenol conjugated to poly(maleic anhydride-alt-1-octadecene)–coated QDs were studied for detection of deoxynivalenol (trichothecenemycotoxin) in diluted extracts of maize with detection limit of 500 µg/L (Speranskaya et al., 2014). More such examples are depicted in Table 15.2.

4.2 Detection of Chemicals and Contaminants

4.2.1 Sensing Preservatives

Food preservatives like benzoates and taste-intensifying additives, such as, glutamates have been checked for their isolation and isotachophoresis zonal electrophoresis detection on a microfluidic poly(methylmethacrylate) chip. The method is very sensitive, with low limits of detection (µM/L) with no interference from food (Bodor et al., 2001). Concentrations of benzoic acid and its salt added as food preservatives are dictated by law, as well as, controlled by regulatory agencies (European Union Law, 1995). Nanomaterial made of glassy carbon electrodes can

Table 15.2 Nanosensors Used for Detection of Toxins

Analyte	Nanomaterial	Detection Method	Detection Limits	References
Aflatoxin B1	Anti-aflatoxin B1 monoclonal Ab–bovine serum albumin immobilized on nanostructured samarium nanorods onto indium–SnO_2–glass substrate	Amperometry immunosensor	57.82 pg/mL with a response time of 5 s	Singh et al. (2013)
Aflatoxin B1	Aflatoxin-oxidase embedded in sol–gel linked to multiwalled carbon nanotubes	Chronoamperometry	1.6 nM with an average response time of 44 s	Li et al. (2011)
Cholera toxin	Anti-cholera-toxin Ab adsorbed on AuNPs modified gold electrode	Change in capacitance	0.09 attoM	Loyprasert et al. (2010)
Clostridium botulinum neurotoxin type A	Dye-doped NP (22 nm) conjugated Ab against nanoporous organosilicate	Fluorescence biosensortoxin	145.8 fg/mL in orange juice and 164.2 fg/mL in tap water	Bok et al. (2013)
Microcystin-LR	Anti-microcystin-LR Ab on QDs	Square wave-stripping voltammetry detection technique	99 ng/L	Yu et al. (2009)
Microcystin-LR	Anti-microcystin-LR Ab on AgNPs used as electrodes	Label-free capacitance immunosensors	10 fM	Dawan et al. (2011)
Microcystin-LR	Anti-microcystin-LR Ab immobilized on gold electrode coated with L-cysteine-modified AuNPs	Label-free amperometric immunosensor	20 ng/L	Tong et al. (2011)
Ochratoxin-A	Anti-ochratoxin A polyclonal Ab bound to AuNPs onto working electrode	Differential-pulse voltammetry	0.2 ng/L	Bonel et al. (2010)
Ochratoxin-A	Rabbit Ab immobilized on nanocrystalline TiO_2-chitosan	Electrochemical impedance spectroscopy	Sensitivity is 7.5 mM, 4 times higher than only chitosan	Khan and Dhayal (2008)

(*Continued*)

Table 15.2 Nanosensors Used for Detection of Toxins (*cont.*)

Analyte	Nanomaterial	Detection Method	Detection Limits	References
Ochratoxin-A	Rabbit IgG Ab-bovine serum albumin immobilized onto nanostructured cerium oxide film fabricated onto an indium–SnO_2	Differential-pulse voltammetry	2.5 ng/L	Kaushik et al. (2009a)
Ochratoxin-A	Rabbit IgG Ab-bovine serum albumin conjugate immobilized on fumed silica NPs and chitosan-nanobiocomposite film	Differential-pulse voltammetry	0.3 ng/dL	Kaushik et al. (2009b)
Palytoxin (marine toxin)	Carbon nanotubes conjugated to anti-Palytoxin Ab	Electrochemiluminescent method	2.2 µg/kg of mussel meat, twofold higher than LC–MS/MS	Zamolo et al. (2012)
Sterigmatocystin	Aflatoxin-detoxifizyme covalently linked to multiwalled carbon nanotubes	Differential-pulse voltammetry	0.13 mM	Yao et al. (2006)
Sterigmatocystin	Aflatoxin-oxidase immobilized onto chitosan–single-walled carbon nanotubes–modified Au electrode	Amperometry	3 ng/mL	Chen et al. (2010)

detect benzoic acid in yogurt and other nonalcoholic beverages. Benzoic acid inhibits the biocatalytic activity of tyrosinase and polyphenol oxidase. Concentrations of benzoic acid up to 0.03 µM could be proportionally detected by catalytic inhibition of tyrosinase entrapped in titania gel modified with multiwalled carbon nanotubes and Nafion in nonalcoholic beverages. The results obtained were consistent with those obtained with HPLC method but with a better sensitivity of 1.06 µA/µM (Kochana et al., 2012). Amperometric quantitation of monosodium glutamate in food seasonings, sauces, and soups using glutamate oxidase anchored to a screen-printed electrode was in the range of 1–20 mg/dL detected within 2 min (Basu et al., 2006).

4.2.2   Sensing the Adulterants

Melamine is an adulterant often found in pet foods, raw milk, and infant foods to elevate the protein content. Cyanuric acid-functionalized AuNPs bind to melamine selectively and cause aggregation of AuNPs, which change in color from red to blue. Limits of detection are 2.5 ppb and the results are easily visible to the naked eye (Ai et al., 2009). Based on a similar principle, chemical reductants and crown ether-modified thiols specific to melamine binding have been included in sensing technology, which prevents formation of AuNPs. This results in a change of color (Kuang et al., 2011). SERS-based detection using patterned gold nanostructures (Bluray Disc surfaces) have also detected melamine up to levels of 2 ppm from contaminated noodles, wheat gluten, cakes and chicken feed (Lin et al., 2008; Liu and Ma, 2010).

Adulteration of urea in milk is an emerging concern. Blends of urease enzyme and polyvinyl pyrrolidone electrospun to form beaded nanofibers of dimensions 7–100 nm were used for urea biosensing. The implantable patch had been originally used for biosensing urea in kidney failure patients, which can also be extrapolated for urea contamination in milk (Gouma, 2010).

Water poisoning with cyanide could be detected up to levels of 2 nM by quenching of fluorescence exhibited by AuNPs (Liu et al., 2010). Detection of acrylamide in water is also possible by voltammetry, using single-walled carbon nanotubes coated on glassy carbon electrodes (Krajewska et al., 2008). Perchlorate, a food and water pollutant, has also been detected using 2-dimethylaminoethanethiol-modified AuNPs based on the SERS principle at 0.1 µg/L (Gu et al., 2009).

Addition of colorants like Ponceau 4R and Sudan I are illegal as they are carcinogenic adulterants (Duncan, 2011). Carbon nanotube-based colorimetric assays have been developed for detection of such food colorants often used in soft drinks and beverages (Zhang et al., 2010). Graphene-modified glassy carbon electrodes detected Sudan IV in ketchup and chili powder in the range of 2×10^{-7} M–8×10^{-5} M (Mo et al., 2010). Multiwalled carbon nanotubes with ionic liquid nanocomposites containing carbon–ceramic electrodes have been used for electrochemical detection of dyes used in food and beverages, such as, tartrazine and sunset yellow (Majidi et al., 2013).

4.2.3   Sensing Heavy Metals

Mercury (Hg) in elemental, inorganic, and organic forms is toxic to humans. Techniques for removal of mercury, cadmium (Cd), silver (Ag), and titanium (Ti) have been developed using superparamagnetic iron-oxide NPs functionalized with dimercaptosuccinic

Table 15.3 Nanosensors in Detection of Heavy Metals

Analyte	Nanomaterial	Detection Method	Detection Limits	References
Cd (II), Co (II), and Sb (III)	Mesoporous silicates conjugated to chalcone isothiocyanate	Color change observed on binding of metals; unbound—pale yellow, Co complex—cyan, Sb complex—yellow, Cd—colorless	Metal ions could be detected from 5 ppb to 1 ppm	El-Nahass et al. (2015)
Hg (II)	AuNPs functionalized with bovine serum albumin conjugated to rhodamine 6G;	Fluorescence response	0.1–2.5 µM	Chai et al. (2010)
	AuNPs functionalized with thioglycolic acid and rhodamine B	Rhodamine B fluorescence is quenched by AuNPs due to FRET, but Hg (II) disrupts the pair	4×10^{-10} M/L consistent with atomic absorption spectroscopy	Zheng et al. (2009a)
Hg (II), Ag (I), and Pb (II)	Fluorescent dye-labeled aptamer is adsorbed on multiwalled carbon nanotube	Fluorescent detection; metals disturb aptamer binding with nanotubes leading to multicolors	Limit of detection of 15 nM for Hg (II), 18 nM for Ag (I), and 20 nM for Pb (II) in water	Wang and Si (2013)

acid from water (Yantasee et al., 2007). AuNPs functionalized with Hg-specific oligonucleotide consisting of thymine can detect Hg (II) up to concentrations of 0.5 nM (Zhu et al., 2009). Monolithic nanostructured cages of cubic Fm3m (C10) monoliths aid in naked-eye detection of toxic metal ions like Hg (II), lead (II), and Cd (Balaji et al., 2006). Detailed reviews of optic sensors for detecting Hg are also reported (El-Safty and Shenashen, 2012). Iron-oxide NPs immobilized with alkaline phosphatase measure the amperometric reaction between alkaline phosphatase and ascorbic acid 2-phosphate on contact with Hg, Cu, Ag, and Pb in water or other complex matrices (Loh et al., 2008). Different nanosensors used for detection of heavy metals are listed in Table 15.3.

4.2.4 Sensing Biocidals

Organophosphates widely used as pesticides and insecticides are retained in plants, water, and fruits due to their high aqueous solubility. They irreversibly inhibit acetyl cholinesterase enzyme,

essential for central nervous system functioning. High consumption causes buildup of the neurotransmitter and interferes with muscular responses and acts as a neurotoxin (Mulchandani et al., 2001). Conventionally, they are detected by chromatography, which is time-consuming and needs trained personnel for extensive preparation steps with no real-time detection. Organophosphorous pesticides can be selectively determined by Ab immobilized on magnetic NPs coated with 3-aminopropyl triethoxysilane based on enzyme-linked immune sorbent assay with high sensitivity (Hu et al., 2010). Acetyl cholinesterase immobilized on copolymer of polypyrrole and polyaniline followed by doping with multiwalled carbon nanotubes could detect thiocholine up to 1.0 ng/mL with good reproducibility. Polypyrrole is used as a polymer matrix as it can be easily electropolymerized in neutral pH solutions at lower oxidation potentials conducive for biologic molecules, while carbon nanotubes provide effective wiring and an anionic dopant. Copolymer of polypyrrole with aniline provided a porous matrix for entrapment of acetyl cholinesterase (Du et al., 2010b). A disposable screen-printed electrode consisting of multiwalled carbon nanotubes with *Drosophila melanogaster* acetyl cholinesterase and Prussian blue detected dichlorvos and carbofuran (organophosphate and carbamate pesticides) up to 0.5 μg/L in vegetable and water samples (Tang et al., 2011).

Residues of herbicide 2,4-D up to 250 pg/mL could be detected using cadmium telluride (CdTe) QD as label. The QD capped with mercaptopropionic acid was coupled to alkaline phosphatase using EDC coupling followed by conjugation to 2,4-D. Competitive binding between conjugated 2,4-D–alkaline phosphatase–CdTe QD and free 2,4-D Anti-2,4-D-IgG Ab immobilized in an immunoreactor column enabled fluoroimmunoassay detection (Vinayaka et al., 2009). Carbon nanotubes and metallic nanomaterial-based electrochemical sensors for detection of pesticide have been reviewed recently (Xiang et al., 2011). Some more examples are cited in Table 15.4.

Crystal violet and malachite green, fungicides, and antimicrobials banned by the US Food and Drug Administration (FDA), are common adulterants found in fish grown in contaminated waters. Patterned gold nanostructures have been able to detect them up to ~0.2 ppb levels based on the SER principle (He et al., 2008).

4.3 Detection of Food Spoilage and Moisture: Food Quality Indicators

Shelf life of food products refers to the period for which they can be used while maintaining the food quality. Extrinsic factors, such

Table 15.4 Nanosensors in Detection of Pesticides

Analyte	Nanomaterial	Detection Method	Detection Limits	References
2,4-Dinitrophenol	AuNPs functionalized with 2,4-dinitrophenol–bovine serum albumin and hybridized with latex microspheres	Colorimetric; competitive binding between conjugated AuNPs and toxin molecules for binding anti-DNP Ab	Rapid detection	Ko et al. (2010)
Chlorpyrifos and malathion	AuNPs	Color change due to pesticide adsorption on AuNP	Chlorpyrifos up to 20 ppb and malathion up to 100 ppb	Lisha and Pradeep (2009)
DDT	Anti-DDT Ab conjugated to AuNPs, nitrocellulose membrane strip immobilized with 2,2-bis-(*p*-chlorophenyl) acetic acid–bovine serum albumin conjugate	Dipstick-based competitive immunoassay; dipping the strip in immunocomplex solution binds to the immobilized Ag with red color formed in detection zone proportional to DDT concentration	27 ng/mL	Lisa et al. (2009)
Methyl parathion	Methyl-parathion degrading enzyme immobilized through CdTe QDs coated on a glassy carbon electrode with multiwalled carbon nanotube and AuNPs	Voltammetry; the enzyme selectively hydrolyzes the P–S bond of pesticide and not any other pesticides; real-time reusable monitoring	1.0 ng/mL	Du et al. (2010a)
Monocrotophos	Glassy carbon electrode modified with CdTe QDs and AuNPs immobilized to acetyl cholinesterase through chitosan microspheres	Voltammetry; QDs and AuNPs synergized and helped in amplifying detection sensitivity	0.3 ng/mL	Du et al. (2008)
N-methylcarbamate pesticide carbofuran	AuNPs labeled to an anti-carbofuran mAb and distributed on porous fiberglass-conjugated pad	Ovalbumin–carbofuran and goat antimouse IgG immobilized on nitrocellulose membrane and works as the test line and control line	0.25 mg/L in water within 10 min	Zhou et al. (2004)
Paraoxon	Paraoxon Ab loaded on AuNPs immobilized on an electrode using Nafion membrane	Voltammetry; electrochemical immunosensor	12 μg/mL	Hu et al. (2003)

as, gaseous atmosphere, storage temperature, and relative humidity coupled with intrinsic properties of food determine the shelf stability and perishability of food. Shelf-stable foods have lower water activity and/or low pH, whereas perishable foods have the opposite intrinsic properties (McMeekin and Ross, 1996). Stale food results in unacceptable flavor, odor, accumulation of gases, release of exudates, physicochemical changes in appearance, consistency, and color.

Stale meat or fish releases gaseous amines like ammonia due to floral growth or any chemical change of the product. Biogenic amines are also indicators of food spoilage (Ruiz-Capillas and Moral, 2004); for example, histamine, putrescine, and tyramine consumption have all been linked to hypertension and migraine (Linares et al., 2012). Xanthines are breakdown products of purines and are used for predicting shelf life of fish and meat (Devi et al., 2012). Xanthine oxidase conjugated to chitosan–ZnO NPs dispersed on a multiwalled carbon nanotube scaffold within matrix of polyaniline was studied as a xanthine sensor. Addition of ZnO NPs to carbon nanotubes promotes better and faster transport of electrons between the active sites of biomolecules (ie, xanthine oxidase and electrode with good chemical stability). Chitosan permitted formation of bioadhesive films for immobilization of xanthine oxidase. The sensor displayed a detection level of 0.1 mM without any interference from matrices (Devi et al., 2012). Conjugation of xanthine oxidase to AgNPs further enhanced the stability of enzymes on storage for 60 days at room temperature (Devi et al., 2013).

Moisture content and gases, especially oxygen in excess, are mainly responsible for food spoilage. ZnO- and TiO_2 NPs have been studied for detection of ethanol and oxygen, respectively (Robert, 2014). Photoactivated indicator ink, consisting of TiO_2- or SnO_2 NPs and redox-active methylene blue dye, detects even trace quantities of oxygen retained during packaging or during leak cases (Mills and Hazafy, 2008). Electrospun nanofibers and nanowebs made of carbon, metal-oxide semiconductors, polymers (nylon-6, polyacrylic acid, and polyvinyl alcohol), and ceramics have been employed as sensors for detection of ammonia, hydrogen sulfide, nitrogen dioxide, carbon dioxide, carbon monoxide, moisture, formaldehyde, and other volatile organic gases (Ding et al., 2010). Adsorption of gases changes the oxidation–reduction potential of oxide semiconductors and affects the electric conductance (Shevade et al., 2003). Polyacrylic-acid nanofibers coated with QCM (Quartz crystal microbalance) exhibit a sensitivity of 130 ppb for the detection of ammonia (Ding et al., 2005). Perylene-based nanofibrils containing fluorophores detect parts-per-trillion level

Table 15.5 Nanosensors in Gas Detection

Gaseous Analyte	Nanomaterial	Observation	References
Carbon dioxide	Fluorophore-encapsulated polymer nanobeads	0.8–100% with 1% resolution and minimal cross-sensitivity of 0.6%	Von Bültzingslöwen et al. (2002)
Ethylene gas	WO_3–SnO_2 nanocomposites (35 nm and 100 nm)	2–8 ppm; WO_3 increased the sensitivity	Pimtong-Ngam et al. (2007)
Gaseous amines	SnO_2 NPs–TiO_2 microrods composites	Conductance changes	Zhang and Zhang (2008)

of gaseous amines (Che and Zang, 2009). A tenside (detergent) film dispersed with carbon-coated CuNPs is also sensitive to humidity. Moisture causes the polymer to swell, resulting in separation of NPs, and hence absorption and reflection of different colors. On dissipation of moisture, the sensors are reusable (Luechinger et al., 2007). Some more examples are given in Table 15.5.

A research team at the Canadian Wheat Board Center for Grain Research has developed sensors for conducting polymeric NPs made of anilineboronic acid-phosphate complex to monitor the quality of grains (Neethirajan et al., 2009). The nanosensors particularly used for carbon dioxide detection essentially consist of anilineboronic acid-phosphate complexes between the gold-interdigitated array microelectrodes and indium-doped SnO_2-coated glass slides and electrolyte layer, followed by a layer of polytetrafluoroethylene as a selective layer. The conducting polymer responds to any volatile gases, insects, fungi, and analytes; detects the source and type of spoilage; and generates a change in electric resistance in the presence of moisture. The sensors have a low power requirement too, and hence can be placed at pest hideouts (Neethirajan et al., 2010; Neethirajan et al., 2013).

4.4   Indicators of Product Acceptability

Standardization of sensory properties (color, smell, taste, and texture) conventionally relies on sensory analysis of trained expertise and thus is subject to human variation, is nonautomatic, and is expensive. Chemical fingerprinting of flavor and aroma is extremely complex and difficult due to the heterogeneity of different compounds, contributing to unique experiences of flavor (smell and taste) (Gardner and Bartlett, 1994). Gas chromatography cannot detect volatile compounds below their threshold limits and needs a time run up to 100 min for a single analysis

(García et al., 2006). Finally, odors perceived are of isolated peaks and not of integral sensation. Electronic nose and electronic tongue are designed similar to the olfactory and taste buds on the tongue and identify variations rather than quantification of any analytes.

Electronic NOSE (Natural Olfactory Sensor Emulator), also known as e-nose, can detect hydrophobic volatile gases having molecular weights in the range of 30–300 Da produced from food products (Reineccius, 1996). E-nose consists of three integrated sections—a sample loading part followed by a sensor and finally a data processing unit. The sample loading part transfers a sample to the sensors. Adsorption of volatiles to the sensor arrays changes the resistance of the sensors proportional to presence of the volatiles and senses specific chemical odors. The sensor arrays are composed of metal-oxide semiconductors, piezoelectric crystals conducting organic polymers, or quartz semiconductors. Polymers with intrinsic conductance, such as, polypyrroles may also be blended with varying sensitivity to analytes. Nonconductive polymers, such as, polyethylene oxide or ethyl cellulose admixed with carbon black may be used (Shevade et al., 2003). Adsorption of volatile gases with high vapor pressure (eg, fatty acids, alcohols formed during bacterial or yeast fermentation) induces oxidation–reduction of oxide semiconductors, changing the dimensions of the composites and affecting electric conductance (Shevade et al., 2003). The data-processing system processes the signals by intelligent pattern recognition algorithms, including discrimination factorial analysis for recognizing unknown samples, principal component analysis, and partial least squares for quantifying bitterness.

Alcohols, fatty acids, esters, and ketones yield strong responses, whereas carbon dioxide, water, and nitrogen dioxide have lower responses. The high surface–volume ratio of nanocarriers favors gas adsorption on sensor arrays and hence increased selectivity and sensitivity of sensors, detectable in a short span of time. It also minimizes the device size and power consumption and simplifies device circuitry. For example, electronic noses can easily detect *Ganoderma boninense*, a plant pathogen responsible for basal stem rot on tree trunks and food products (Abdullah et al., 2011; Durán and Marcato, 2013).

As described earlier, an electronic nose based on polymeric NPs of polyanilineboronic acid has been demonstrated for detecting ongoing spoilage during storage of grains (Neethirajan et al., 2013), as well as, discriminating strains of species producing mycotoxins and mold from healthy grains (Magan and Evans, 2000). A number of reviews on the same with details can be referred (Cabanes et al., 2009; Sahgal et al., 2007).

Cyranose 320 (Cyrano Sciences, Pasadena, CA) is a commercial handheld electronic nose consisting of nanocomposites of conducting polymers, for example, poly(vinyl butyral) and poly(ethylene oxide), with carbon-black nanotubes with advanced pattern recognition algorithms. For identification, the instrument has to be trained to associate and store smell prints of each volatile with distinct responses (Gouma and Sberveglieri, 2004). Cyranose 320 detects *Salmonella*, *E. coli*, and *S. aureus* in beef and sausages at concentrations from 50 ppb onward (Balasubramanian et al., 2005; Abdallah et al., 2013). It gives simple results, such as, "Accept" or "Reject," "Mixture Identified," or "Contaminated." Sensitivity and specificity of an electronic nose detecting *E. coli* O157:H7 and non-O157 strains ranged between 41.7% and 50% for nonnormalized data (Younts et al., 2003). Libra Nose is also a metalloporphyrin-coated quartz microbalance sensor array-based electronic nose for detection of alcohols, amines, ketones, and aromatic compounds (Di Natale et al., 2003).

Metalloporyphyrins mimic the mammalian olfactory receptors, which are also metalloproteins in nature. Chemical selectivity and sensitivity of sensors depend on metal and peripheral constituents of the complex (Brunink et al., 1996). Microfabricated beams of silicon (cantilevers) coated with polymer are also nanomechanical sensors for detecting volatile gases. Interaction of volatile gases results in swelling of the polymer, and the surface stresses cause bending of the cantilever or change in resonating frequency for cantilevers in static or dynamic mode (Gouma and Sberveglieri, 2004). Nano-ZnO film gas sensors evaluated quality of Chinese vinegar. ZnO NPs are sensitive to hydrogen sulfide, nitrogen dioxide, chlorine, ozone, and alcohols at room temperature. This is a unique feature compared to headspace gas chromatography, which requires heating to achieve equilibration of volatile gas in the headspace (Zhang et al., 2006). Few nanosensors can detect gases released from food products that are not suitable for consumption due to spoilage (Valdés et al., 2009; Ghasemi-Varnamkhasti et al., 2011; Śliwińska et al., 2014).

Quality of food can also be differentiated using nanosensors (Durán and Marcato, 2013). An electronic tongue responds to soluble portions of food using an array of sensors combined with pattern-recognition analysis. The pattern obtained is matched with the existing database of tastes. Electronic tongues are composed of layer-by-layer ultrathin films of molecular building lipid/polymer membranes with 10,000-fold increased sensitivity than that of the normal human tongue. Molecular assemblies of polyhydroxyl groups and association of sodium ions at particular pH decide the tastes of particular foods. In the presence of analyte, the building block

self-assembles and forms receptors (Hou et al., 2012). The electrode charge density of the lipid/polymer membrane and ion distribution changes and gives a particular membrane electric potential, or SPR imaging measures molecules adsorbed by receptors for food.

Receptors for bitterness have been immobilized on polypyrrole-modified carbon nanotubes. Upon binding, polypyrrole reorients, which is recorded as an electric signal. Bitterness up to 1 fM could be detected in beverages (Song et al., 2012). Discrimination of degradation products in orange juice has been efficiently detected using microelectrodes of polyanilinenano fibers used as taste sensors (Medeiros et al., 2009). The electronic nose and tongue replace the human sensory test for quality determination, which often fails on routine and repeated analysis.

A number of glucose-sensitive sensors have been developed for determining glucose content in commercial beverages (eg, AuNPs coated with glucose-sensitive enzymes) (Ozdemir et al., 2010). *Pseudomonas fluoresens* immobilized on carbon nanotubes with epoxy composite could detect 0.5–4.0 mM of glucose and xenobiotics in anaerobic conditions with high sensitivity (Kirgoz et al., 2007).

4.5   Others

4.5.1   Detection of Veterinary Drugs

Animals treated with veterinary therapeutic products are exposed to wide range of chemicals legally or illegally. Majorly, they include antimicrobials used in treatment of infectious diseases or to enhance growth rates or feed efficiency. Residues of these chemicals, especially antibiotics in milk and poultry livestock, including penicillin, tetracycline, macrolides, and β-lactam, pose as toxic hazards, lead to allergic responses, or to the development of antibiotic-resistant strains in the poultry, as well as, in humans consuming them (Ferrini et al., 2008). Chloramphenicol molecularly imprinted poly(ethylene glycol dimethacrylate-*N*-methacryloyl-L-histidinemethylester) NPs attached onto the surface of SPR detected 40 ng/kg of chloramphenicol in a honey sample. The method was verified to be selective with thiamphenicol and florphenicol with similar chemical structures (Kara et al., 2013). Anti-penicillin G immobilized on gold electrode modified with a self-assembled nanolayer of thioctic acid detected 3×10^{-15} M of penicillin G in milk by impedimetry (Thavarungkul et al., 2007). Tobramycin could be detected by QCM nanosensor of gold surface containing a self-assembled monolayer of mercaptane up to a concentration of 5.7×10^{-12} M in chicken egg white and milk (Yola et al., 2014).

4.5.2 Detection of Nutritional Components

Lysine is used as marker for nutritional damage caused in food products due to heat treatment, for example, ultraheated temperature (UHT) treated milk. The estimation of lysine in processed food products, based on advanced "Maillard reaction," gives an indication of the protein damage due to food processing. Lysine has a free ε-amino group that can easily react with other reducing sugars present in food as ingredients. This reaction gives a specific color and flavor to food when heated to a high temperature, which acts as an indicator (Luong et al., 1997). A detection system based on biotin-labeled Ab, coupled with an enhanced chemiluminescence or fluorescence, detects protein present in analytes (Luong et al., 2008).

A quick, reliable, and sensitive immunodipstick colloidal gold coated with vitamin B12–IgY Ab has been developed for vitamin B12 measurement in food samples. The visible detection limit of vitamin B12 is 1 ng/mL. This immunodipstick probe is simple and effective with no requirement of trained operators. Vitamin B12 is essential for normal functioning of the neural system and brain. This is of special note for vegetarians, as plant products are deficit in vitamin B12 (Selva Kumar and Thakur, 2011).

Certain food products (eg, poultry, meat, cheese, and shrimp) are characterized by high amounts of cholesterol. They can also be quantified using carbon nanotubes. These carbon nanotubes have polymer enzyme coatings. Carbon nanotubes increase the electrocatalytic effect due to enhanced surface coverage area for measurement of electrocatalytic response using voltammetry. Carbon nanotubes promote electron transfer reactions in redox reactions (Yang et al., 2011b; Wisitsoraat et al., 2009). An online database has also reported infusing nanocapsules of plant steroids replacing meat cholesterol (Mulvaney, 2011). Some of the other nanobased systems to determine nutritional content are given in Table 15.6.

4.5.3 Detection of Growth-Promoting Agents and Steroids

Plant growth-promoting agents and steroids are used in food production and livestock reproduction, respectively, to gain maximum profits with minimum investments. However, consumption of these steroidal hormones puts humans at risk, while growth-promoting agents accumulate along the food chain in fatty tissues, and it is difficult to rid consumers' systems of the substances for a prolonged time. For example, tests are conducted to estimate progesterone in milk and other food products originating from farm animals. These diagnostics are primarily immunoassay-based techniques (Tothill, 2001). Improved versions of immunosensors

Table 15.6 Nanosensors for Detecting Nutritional Components

Analyte	Nanomaterial	Detection	Observation	References
Glucose	Graphite rod electrode modified by AuNPs containing glucose oxidase	Amperometric enzyme electrode	Linearity range 0.1–10 mM, detection limit 0.08 mM	German et al. (2010)
Glucose	Polyamide nanofibrous membrane coated on glassy carbon electrode containing glucose oxidase	Amperometric enzyme electrode using ferrocene as mediator	Linearity range 1–10 mM with detection limit of 6×10^{-6} M	Scampicchio et al. (2010)
Inulin	Fructose dehydrogenase and inulinase immobilized on a AuNPs–cysteamine self-assembled monolayer, modified gold electrode	Inulinase hydrolyzes inulin forming fructose detected by fructose dehydrogenase by electrochemical oxidation of tetrathiafulvalene used as mediator	Lifetime of sensor is 35 days with detection limit of 6.6×10^{-7} M/L	Manso et al. (2008)
Oxalic acid	Multiwalled carbon nanotubes modified glassy carbon electrode	Voltammetry; oxidation of oxalic acid was greatly improved over bare glassy carbon electrode	Detection limit 0.012 mM	Zheng et al. (2009b)
Phenolic compounds	Tyrosinase immobilized by drop-coating on glassy carbon electrode by polyamidic nanofibrous membrane	Amperometry	Response time of 16 s with a detection limit of 0.05 μM	Arecchi et al. (2010)
Polyphenols	Tyrosinase immobilized on carbon electrodes with electrodeposited AuNPs	Voltammetry	Lifetime of 18 days; rapidly detects phenol, catechol, caffeic acid, chlorogenic acid, gallic acid, and proto-catechu aldehyde in wines	Carralero Sanz et al. (2005)
Polyphenols	Laccase biosensor on a multilayer material of AuNPs, fullerenols, and *Trametes versicolor* laccase assembled layer by layer onto gold electrode surface	Amperometry	Limit of detection of 0.006 mM/L in wine expressed as polyphenol index 5.0–50 mg/L	Lanzellotto et al. (2014)

that are based on nanotechnology are required for on-site and real-time monitoring of food products, which are still in the nascent stage.

A detailed explanation of various growth-promoting agents in agricultural crops, such as, pesticides and insecticides is already covered in Section 4.2.4. Nanobiosensors composed of an atomic-force microscopy tip functionalized with acetolactate synthase enzyme detected the herbicide metsulfuron-methyl, an acetolactate synthase inhibitor, through force curves (Sekhon, 2014). Misuse of clenbuterol, used for treatment of asthma, for increasing the fat and protein in pigs has led to development of a florescence-based immunoassay. This assay, consisting of CdSe/CdS QDs and Fe_3O_4/AuNPs for Ag–Ab attachments, can estimate clenbuterol in the linear range of 0.5–20,000 pg/mL in pig urine (Wang et al., 2009b).

4.5.4 Detection of Food Allergens

Food allergens are food components that on consumption trigger allergic reactions that could range from minor skin rashes to severe, life-threatening conditions. Examples of major potential allergens include peanuts, wheat protein gluten, milk, egg, nuts, shellfish, and soybeans. The European Community has identified 14 allergenic food ingredients as food allergens and has fixed regulations for labeling them (Pilolli et al., 2013). Food allergy is described as an immune response that could be genetic or environmentally induced, and is IgE mediated or non-IgE mediated (cellular), involving oral, gastrointestinal, and respiratory tracts.

Evaluations of IgE-based hypersensitivity due to peanut protein Ara h1 using AuNPs localized plasmon array have been studied up to a detection limit of 2 nM (Olkhov et al., 2012).

Soy protein, a major food allergen of soymilk, soy yogurt, fruit, and soy juice, has been detected by silica NPs doped with Nile blue (particle size 257 nm). Nile blue-doped silica NPs prepared by reverse-micelle microemulsion and linked to antisoy protein Ab detected soy protein up to 0.05 mg/L with an incubation time of 2 h (Godoy-Navajas et al., 2011).

Egg-white protein (ovalbumin) added to whole milk can be detected up to 1 ppm within 20 min by combined technology of immunomagnetic separation of ovalbumin by magnetic microbeads followed by SERS using silver dendrites for quantitation (He et al., 2011). SPR-based techniques are coupled with sensors for quantification of α-lactalbumin present in marketed milk and whey protein isolates (Indyk, 2009). Adulteration of bovine and caprine milk with colostrum has been reported using an IgG-based SPR immunosensor with a short analytical real-time monitoring time of within 4 min during milking (Pilolli et al., 2013).

Table 15.7 Nanosensors Used in Detecting Food Allergens

Analyte	Nanomaterial	Detection	Observation	References
Casein	Ab-coated AuNPs + Poly(L-Arg)/multiwalled carbon nanotube	Differential-pulse voltammetry	50 ng/mL in cheese	Cao et al. (2011)
Chicken ovomucoid	Concanavalin A conjugated zinc oxide QDs sized 3 nm	Square-wave voltammetry	1 ng/mL in standard solutions	Yang et al. (2011a)
Gliadin	Ab-coated AuNPs (25 nm)	QCM	8 ppb in standard solutions, food matrix wheat, barley, oat, rice, corn, and soybean pancake mix—1 ppm	Chu et al. (2012)
Peanut protein Ara h1	Ab-coated 3 nm Au-coated nanoporous membrane	Electrochemical impedance spectroscopy	—	Singh et al. (2010)
Shrimp	Ab-coated AuNPs (10 nm)	QCM	0.33 µg/mL in spiked water samples	Jiang et al. (2013)

Quantitative determination of bovine serum albumin, immunoglobulin G, α-lactalbumin, β-lactoglobulin, and lactoferrin simultaneously in milk, whey fractions, and milk-derived products is possible using SPR (Billakanti et al., 2010). Imaging SPR with Ab array provided a complete allergen profile of hazelnut content in cookies and chocolate products (Rebe Raz et al., 2010). Some other examples are also given in Table 15.7.

4.5.5 Detection of Genetically Modified Food

Recent developments in genetic engineering and its application in crop production to meet the demands of ever-increasing global population have put many in a dilemma about its use in food production (Sicherer and Sampson, 2010). Considering regulatory aspects related to food products of genetically modified (GM) organism origin, a thorough assessment is thus required for risks related to consumption of these products. Sociopsychological aspects affect the acceptability of GM foods. Protein analysis

by using immunosensors accounts for one of the growing markets in the food industry. SDI Europe Ltd. has developed an immuno-assay that can detect GM food ingredients using dipstick devic-es. Detection of GM food products that are consumed by either humans or animals are based on PCR techniques that analyze specific DNA sequences. These developments have led to minia-turization of the instruments that were previously used in labora-tories and are now available for on-site analysis of samples using DNA chips. These tests can also be modified into DNA biosensor devices (Tothill, 2001). SERS-barcoded nanosensors designed by encapsulation of AuNPs with silica conjugated to oligonucleotides detected *B. thuringiensis* (Bt) gene-transformed rice expressing insecticidal proteins up to 0.1 pg/mL (Chen et al., 2012).

5 Advanced Packaging Quality

A turning point in packaging is nanoreinforced packaging and active packaging providing an extra tensile strength of food packets. Nanosilver in combination with antibacterial agents may prove to be more potent to combat multiple bacterial growths with a smaller amount of dose required. TiO_2 has been suggest-ed to improve upon the UV protection barrier, as well as, reduce bacterial contamination in food packaging when used as NPs (Ranjan et al., 2014). Several antimicrobial packaging and oxygen-scavenging food packages have been developed (Saxl, 2011). Imperm (Eastman Chemical Co., Kingsport, TN, USA), Aegis, Durethan, and others use a nanocomposite of nylon and nano-clay with enhanced barrier properties that can help keep the oxy-gen out and the carbonation in, especially in polyethylene bottles. Beer in nanocomposite bottles can keep for as long as 30 weeks. The same has also been used in soda, milk, and water bottles, as well as, in military food packages (Gruère, 2012). Milk packages made of these materials improved durability of milk up to 9 days, and grains stayed dry. Nanowax for fruits also provided better durability and transparency (Sekhon, 2014).

Aegis OX (Honeywell, Inc.) has oxygen scavengers and nano-composite clay particles within the polyethylene bottle material for fruit juice, soft drink, and beer servings. Durethan KU2-2601 (Bayer AG), composed of polyamide and nanoclay with layered silicate barriers, with enhanced gloss and stiffness, in addition to barrier properties, is commonly used in paperboard juice con-tainers (Ranjan et al., 2014). Nanolok, a polymeric resin composed of nanodispersed silicate, generated superabsorbent-hydrogel nanocomposites. The McDonald's burger containers contain an

ecosynthetic adhesive made up of 5–150 nm starch nanospheres, which require less water for adhesion with reduced drying time (Kumari and Yadav, 2013).

Incorporation of enzymes, such as, cholesterol reductase or lactase increases the nutritional value of food. SiO_2 NPs immobilized with glutamate dehydrogenase and lactate dehydrogenase have shown enhanced enzyme activity (Ranjan et al., 2014).

6 Smart Food Packaging Sensors

Smart- or intelligent packaging indicates the quality of food within a package through use of intelligent nanosensors devices that are either incorporated into packaging or attached to packaging (ie, nanocomposite smart packaging). For instance, incorporation of oxygen scavengers or indicators within food packaging material would serve as indicators for food spoilage by sensing gaseous analytes and thus provide real-time food freshness (Lange et al., 2002; García et al., 2006). Food-packaging distributors also use nanotechnology-based biosensors for product tracking (nanotagging) by using radio-frequency identification tags to prevent counterfeiting. However, radio frequency identification tags are expensive, with the cheapest tag costing about 50 cents. Optic fibers also find wider application with calorimetric and florescent dyes that change florescence and absorbance with a change in pH or oxidation state.

Motivations to innovate new technology related to the food sector are consumer demands for quality food products globally and the need for faster transport of food. Purposes of packaging are to retard food deterioration, increase in shelf life and provide protection from environmental influences, such as, light and moisture. There are materials that change color on exposure to visible- or UV light, indicating the quality of the food product. This technology when coupled with information and communication technology can automatically send data to users or monitoring sections about the condition of food products. This combination can revolutionize the world of the packaging industry both at the consumer level and at the industry level. For example, substances that are produced due to food spoilage processes (lactic and acetic acids, alcohols, and amines) can be detected by the use of smart-packaging materials made of luminescent nanosized ZnO and organic luminophores. These nanophotonics assemblies can work as novel packaging materials. The principle involved behind this novel packaging is that it detects the change in properties (optic, electric, or mechanical) of sensors. These changes can be analyzed by visual inspection or by external devices that convert the packaging

response into electric signals followed by data interpretation using computer systems. This combination of smart packaging with communication technology is cost-effective and utilizes photonics principles at the nanoscale level. This innovative technique of detection is termed nanophotonics with detection limits of 2×10^{-3} M/L for ZnO and 10^{-5} M/L for organic luminophore (Sarapulova et al., 2015).

Timestrip has developed an iStrip based on AuNPs that shows red color at temperatures above freezing. Freezing causes irreversible agglomeration of the AuNPs with loss of red color. Thus accidental exposure of chilled foods to room temperature could be determined using this iStrip. Various TiO_2- and SnO_2-based colorimetric oxygen indicators have been developed that bleach the color of redox dyes on exposure to UV irradiation. The color of the films developed depends on the extent of exposure to oxygen (Ranjan et al., 2014).

Nanobarcodes consisting of synthetic DNA barcodes present in film packages detect the food pathogens by fluorescence of a fluorescent probe under UV (Brody et al., 2008). GuardIN Fresh, a Nanomech subsidiary (Fayetteville, AR, USA), commercializes a nanotechnology-based scavenging system that scavenges ethylene gas responsible for hastened ripening of perishable products (Sekhon, 2014). An electronic tongue has also been used in food packaging to detect gases released due to spoilage of food. The gases cause the sensor strip to change its color in the presence of gases, indicating whether the food is fresh or stale (Saxl, 2011).

A research group at Netherlands is working on "Release on Command" food packaging with a nanobased bioswitch that releases preservatives when the food is about to spoil (Sekhon, 2014). Such sensing mechanisms would not only improve the food quality but also reduce food wastage.

7   Regulatory Aspects

Stringent regulatory guidelines must to ensure "safe" and "quality" food to consumers. There has been a lack of regulatory guidelines on the use of NPs in food packaging and storage at the US Food and Drug Administration. This needs to be taken seriously, as lack of guidance will hamper both the growth and the application of nanotechnology in the food industry (Servin et al., 2015).

Nanocomposites, the earliest commercial application in the food industry, include use of plastic nanocomposites applicable for packaging of food and beverages. Commercial biosensors based on nanocomposites are concise, simple, and easy to use

for point-of-care biosensing. There are diagnostic assays that are fabricated using nanosensors for point-of-care assessment of Ab in milk samples, but they are not commercially available for field testing. Research is ongoing to make them available for testing on farm animals using nonserological milk samples (Vyas et al., 2015). Cellulosic nanowhisker production technology has been developed to replace the use of plastic and fiberglass, by making biocomposite from wheat straw. Nanobarcode technology has gained momentum in the past few years because of its ability to form a large number of combinations. But this technology is not yet well exploited (Dasgupta et al., 2015). Inorganic materials like SiO_2, MgO, and TiO_2 are being used as coating materials for used as oxygen barriers, and Ag for "active coating" for antibacterial activity (Chaudhry and Castle, 2011).

8 Future Aspects and Challenges

Nanocomposite technology is an emerging material science. Its wider application in the food industry extends from food production to food processing and ultimately to food consumption. Tracing food products, quality assessment, safety, and maintaining a nutritional index have all made the food industry take a deeper look into technology involved in innovative diagnostics and biosensing techniques. On-site and point-of-care detection for a large number of increasing analytes requires quick, sensitive, and accurate measurements. This has inspired many researchers in the food industry to develop nanotechnology-based sensors as diagnostic tools. Nanotechnology-based biosensors using nanocomposites will reduce the load of laboratory testing and provide on-site applications. There is an urgent need for more available technology in the food industry for easy, affordable, sensitive, and broad-spectrum analysis of food products, both at industrial level and at consumer level. This chapter has specifically emphasized developments in the field of nanotechnology-based biosensors being incorporated in food industry for detection of plant-based pathogens, toxins, GM food products, nutritional index, and regulatory aspects attached to them.

A major challenge with nanobiosensors is their use with real samples, as many biosensors fail when they come in contact with real food products because of the complexity of samples. Replacement and recalibration of nanobiosensors are another drawback that needs to be considered. Nanobiosensor-based on-site tests help in reduction of time for which products are kept in inventory, rapid response time and corporate liability costs (Alocilja and Radke, 2003).

Most of the research is still in its nascent stage for detection of analytes in real food without disrupting its final form. A nondestructive technology based on information directly available on the final packed food product would be very desirable. SPR-based sensors are a promising technique that does not require labeling with molecules and can easily assay crude samples without purification. The need for nanobiosensors has multiplied many fold in the recent past due to increased consumer awareness and regulatory action being imposed about food composition and safety.

Abbreviations

Ab   Antibody
AuNP   Gold nanoparticle
CFU   Colony-forming unit
NP   Nanoparticle
QD   Quantum dot
SERS   Surface-enhanced Raman scattering
SPR   Surface plasmon resonance
SQUID   Superconducting quantum interference device
QCM   Quartz crystal microbalance

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