THE INTERNATIONAL JOURNAL OF SCIENCE & TECHNOLEDGE

Nanosensors and Their Applications in Food Analysis: A Review

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Abstract:
A convenient, quick and cost-effective method for analysing the food for presence of biological or chemical component is one of the greatest challenges confronting the food processing industry. Nanosensors are emerging as highly promising tools for the purpose as they offer significant improvements in selectivity, speed and sensitivity compared to the chemical or biological methods used traditionally. Nanosensors can be used to determine microbes, contaminants, pollutants, etc. and ultimately the freshness of the food. This manuscript reviews the different types of nanosensors used for food analysis and their mechanisms of action in different foods. This information on nanosensors can be exploited to develop new sensor materials and technologies.

Keywords: *Nanosensor, food analysis, nanoparticles, electrochemical, optical, quality*

1. Introduction

Nanoscience and nanotechnology have already found their way into various fields such as computer electronics, communication, energy production, medicine and food processing due to their multifarious applications. The application of nanotechnology to the agricultural and food industries was first addressed by the United States Department of Agriculture in its roadmap published in September 2003 (USDA, 2003).

In the food industry, several novel applications of nanotechnologies have become apparent, including the use of nanoparticles, such as micelles, liposomes, nanoemulsions, biopolymeric nanoparticles and cubosomes, as well as the development of nanosensors, which are aimed at ensuring food safety (Yih *et al*., 2006; Esposito *et al*., 2005; Ligler *et al*., 2003). Nanosensors are extremely small devices, with dimensions in the order of one billionth of a meter, capable of detecting and responding to physical stimuli. This capability of nanosensors can be used beneficially for food analysis by utilizing them for detection of pathogens, toxins, nutrients, environmental characteristics, heavy metals, particulates, allergens, etc. using different mechanisms. Various researchers have reported different mechanisms to exploit the advances in nanosensors for food analyses (Chen *et al*., 2004; Haruyama, 2003; Jain, 2003; Vo-Dinh *et al*., 2001).

The aim of this article is to provide an overview of the different types of nanosensors used for food analysis and the mechanisms used by them.

1.1. Nanosensors

Nanosensors are nanoscale devices built with cross sections of about 10 nm and masses of a few attograms (10^{-18} g). They are manufactured with the view to imitate the nanomaterials found in nature including proteins, DNA, membranes and other natural biomolecules which can detect minute changes in the foods through different mechanisms (Sanguansri and Augustin, 2006; German *et al*., 2006).

There might be a possible confusion between nanosensors and biosensors. Hence it is necessary to address the relation between the two. Biosensors are devices that use biological components to react or bind with a target molecule and transduce this event into a detectable signal (Nath *et al*., 2004a, 2004b). A nanobiosensor is a biosensor on the nano-scale size.

Since the nanosensors used in food analyses use a combination of biology and nanotechnology, the nanosensors may also be called nanobiosensors. Some salient features like sensitivity, specificity, rapidity of testing and other necessary attributes of biosensors are improved by using nanomaterials in their construction (Jin *et al*., 2003).

These features of nanosensors provide wide scope for their applications in food analysis operations like inspection of raw materials, on-line process control, monitoring of storage conditions etc. Besides serving as cost effective tools the nanosensors could provide immense improvements in quality control, food safety, and traceability.

1.2. Need for Nanosensors

Fresh food products which are spoiled exhibit odours, colours or other sensory characteristics which can be easily discerned by consumers. But when the foods are packed, the packaging material prevent sensory exposure from the foods and hence consumers must rely on expiry dates provided by producers based on a set of idealized assumptions about the way that the food is stored or transported. However, if the

transport or storage conditions are violated for any period of time, the actual quality of food might be deteriorated which might not be known to the consumer unless the food package is opened, or even consumed.
Nanosensors offer solutions to this problem through their unique chemical and electro-optical properties. It has been found that nanosensors are able to detect the presence of gasses, aromas, chemical contaminants, pathogens, and even changes in environmental conditions. Thus nanosensors could not only ensure that consumers purchase products which are at their peak of freshness and flavour, but also reduce the frequency of food-borne illnesses. Hence nanosensors are needed to improve overall food safety.

1.3. Nanosensors for Food Analysis
Nanosensors are applied in varied areas in food sector for the purpose of analysis as shown in Figure 1.

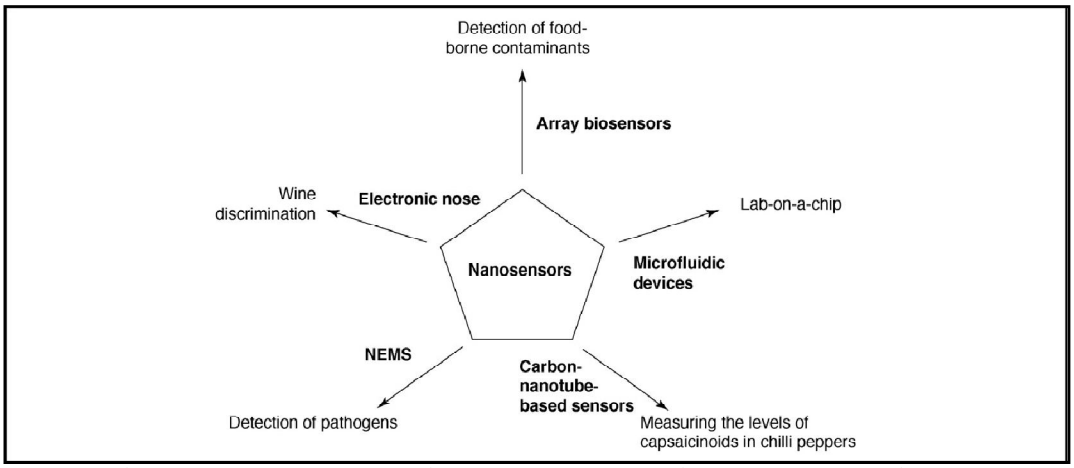

Figure 1: Types of nanosensors and examples of their application in the food sector (Adapted from Sozer et al., 2008)

In the food analysis market, biosensors produced by two technologies viz., microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS) are prevalent. A digital transform spectrometer (DTS) produced by Polychromix (Wilmington, MA, USA) uses microelectromechanical systems technology to detect trans-fat content in foods (Ritter, 2005).
Nanosensors produced with the nanoelectromechanical systems (NEMS) technology contain moving parts ranging from nano- to milli-meter scale, which might serve as developing tools in food preservation. They can control the storage environment and act as active 'sell by' devices. NEMS could be used in food quality-control devices because they consist of advanced transducers for specific detection of chemical and biochemical signals. These technologies are still at a very early stage of development but research is rapidly gaining momentum and a growing number of NEMS-based sensors are appearing in the literature.

1.4. Different classes of Nanosensors
When it comes to applications in food analysis, there are three main classes of nanosensors.

1. Nanoparticle based sensors
2. Electrochemical nanosensors
3. Optical nanosensors

2. Nanoparticle Based Sensors
Nanoparticles in food may appear in suspensions (mostly solid in liquids) or emulsions (two liquid phases). Nanoparticles of complex nanoscale structures are reported to be used as nanosensors in packaging to detect food deterioration and they are also used in hand held devices for monitoring storage conditions and detection of contaminants (Bouwmeester *et al*., 2009). Within the agro-food chain, metal or metal-oxide nanoparticles are largely applied (e.g., nano-Ag, nano-ZnO, nano-Cu, nano-TiO_2) for purposes like detection of organic molecules, gases, moisture, micro organisms etc.

2.1. Detection of Small Organic Molecules
Nanosensors have the potential to revolutionize the speed and accuracy with which industries or regulatory agencies can detect the presence of molecular contaminants or adulterants in complex food matrices. Many of these assays are based on observed colour changes that occur to metal nanoparticle solutions in the presence of analytes. For example, gold nanoparticles (AuNPs) functionalized with cyanuric acid groups selectively bind to melamine (Fig. 2), an adulterant used to artificially inflate the measured protein content of pet foods and infant formulas; the melamine-induced aggregation causes AuNPs to undergo a reproducible, analyte-concentration-dependent colour change from red to blue, which can be used to precisely measure the melamine content in raw milk and infant formula at concentrations as low as 2.5 ppb with the naked eye (Ai *et al*., 2009).

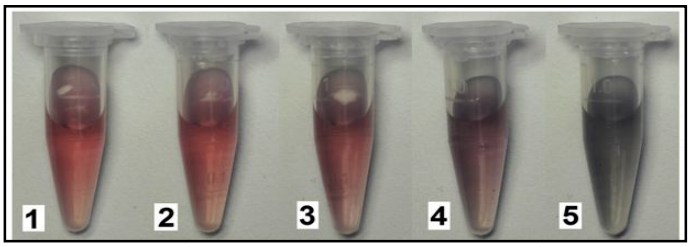

Figure 2: Schematic showing colorimetric detection of melamine in solution using modified gold nanoparticles (AuNPs). (1) AuNP solution without any addition; (2) with the addition of the extract from blank raw milk; (3), (4) and (5) with the addition of the extract containing 1 ppm (final concentration: 8 ppb) melamine, 2.5 ppm (final concentration: 20 ppb) melamine and 5 ppm (final concentration: 40 ppb) melamine, respectively (Adapted from: Ai et al., 2009)

Some assay systems for small molecules depend on fluorescence rather than absorptive color changes. For instance, a sensor based on a detection methodology called enhanced fluorescence linked immuno-sorbent assay (EFLISA) can be used to detect the presence of gliadin and gluten content of gluten-free foods. This could also be easily adapted for the selective detection of other protein-based analytes (Staiano *et al*., 2009).

Another fluorescence-based assay efficiently detected cyanide in drinking water at concentrations as low as 2 nM using fluorescence quenching of gold nanoclusters (Liu *et al*., 2010). Several protein-based bacterial toxins (Goldman *et al*., 2004), including bolutinum toxin serotype A (Warner *et al*., 2009), have been detected at picomolar (pM) levels using antibody-labeled luminescent quantum dots, which would be useful in food safety and anti-bioterrorism applications. These techniques used by nanoparticles based sensors could be devised for the convenient analysis of foods for adulterants, allergens or contaminants.

2.2. Detection of Gases

Oxygen content in food is a primary factor which favours the growth of microorganisms. For the purpose of testing the gaseous constituents, the packages of the packed food are destructed. In processing facilities, packaged foods are tested randomly during a production run, which is time-consuming, costly and yet unreliable. A non-invasive method to continually and easily monitor the gas content of a package headspace would provide a means to ensure the safety and quality of the contained food long after it has left the production facility (Arndt, 2008).

On this view, a promising photoactivated indicator ink for in-package oxygen detection based upon nanosized TiO_2 or SnO_2 particles and a redox-active dye (methylene blue) has been developed (Mills, 2005; Lee *et al*., 2004; Lee *et al*., 2005; Mills *et al*., 2009). This detector gradually changes colour in response to even minute quantities of oxygen, as shown in Fig. 3. Though quantification of the oxygen content within food packages might not be possible by this technology, it nevertheless provides consumers and retailers an easy, visual method to identify modified atmosphere packages (MAPs) with possible compromised seal integrity.

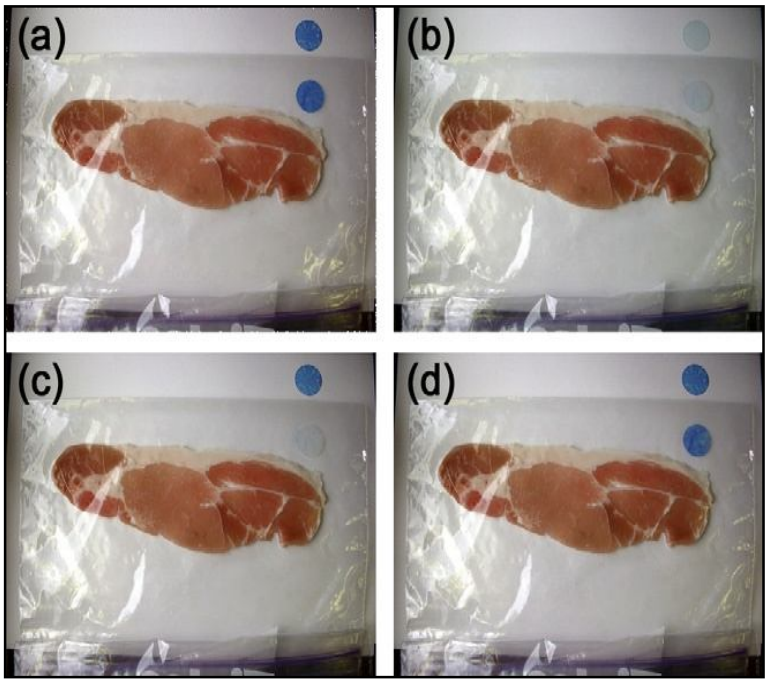

Figure 3: Photographs of O_2 sensors which utilize UV-activated TiO_2 nanoparticles and methylene blue indicator dye, one placed inside of a food package flushed with CO_2 and one placed outside. In (a) the package is freshly sealed and both indicators are blue. The photograph in (b) shows the indicators immediately after activation with UVA light. After a few minutes, the indicator outside of the package returns to a blue color, whereas the indicator in an oxygen-free atmosphere remains white (c) until the package is opened, in which case the influx of oxygen causes it to change back to blue (d). This system could be used to easily and noninvasively detect the presence of leaks in every package immediately after production and at retail sites (Adapted from: Mills, 2005)

A non-invasive method of measuring carbon dioxide content in MAPs has also been devised, and is based upon lifetime analysis of luminescent dyes standardized by fluorophore-encapsulated polymer nanobeads (Bultzingslowen *et al*., 2002). This CO_2 sensor has a detection range of 0.8–100%, a resolution of 1%, and only 0.6% cross-sensitivity with molecular oxygen. Some other examples of gas sensing related to food safety or quality include: detection of gaseous amines, which are indicators of fish and meat spoilage (Hernandez-Jover *et al*., 1997), WO_3-SnO_2 nanocomposites to detect the presence of ethylene gas, a hormone responsible for fruit ripening (Pimtong-Ngam *et al*., 2007).

2.3. Detection of Moisture

Nanosensors based on nanoparticles have also been developed to detect the presence of moisture content inside a food package. Such a nanosensor for moisture content, as shown in Fig. 4, is based upon carbon-coated copper nanoparticles dispersed in a tenside film (Luechinger *et al*., 2007). In humid environments, swelling of the polymer matrix results in larger degrees of inter-nanoparticle separation; these changes cause sensor strips to reflect or absorb different colours of light which can be monitored easily for quick and accurate determination of package moisture levels without invasive sampling.

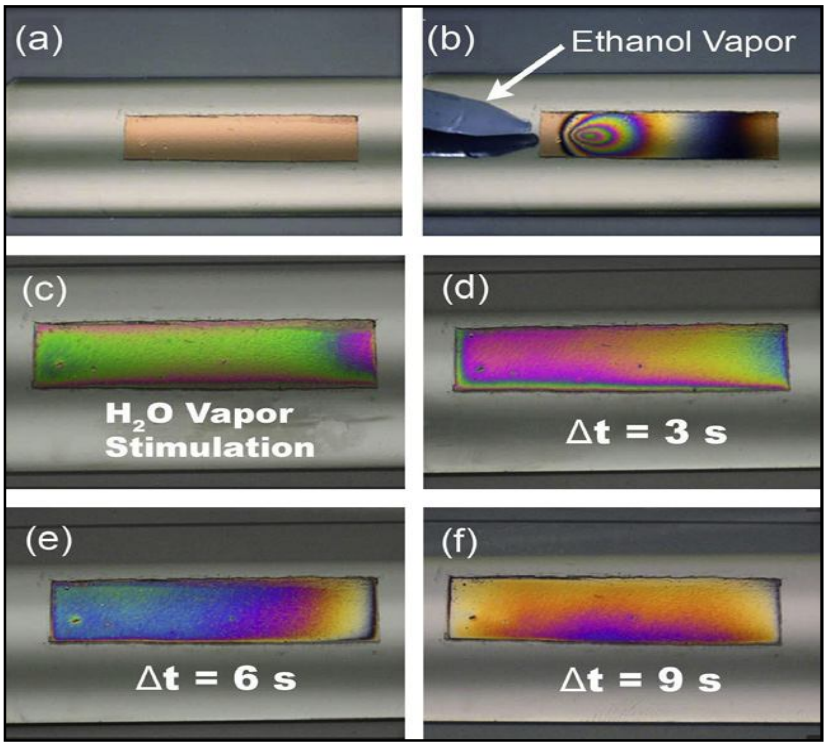

Figure 4: Moisture sensor which utilizes carbon-coated copper nanoparticles dispersed in a polymer matrix (a). Ethanol vapor exposure results in rapid and reversible iridescent coloration (b). Water vapor exposure swells the polymer, which causes the nanoparticles to exhibit larger interparticle separation distances and thus different observable optical behavior (c). As moisture dissipates (d–f), the sensor reverts back to its native state and appearance (Adapted from: Luechinger et al., 2007)

2.4. Detection of Microorganisms

The ability to determine whether food products are contaminated by various bacteria, fungi or viruses remains an important research objective. Most detection strategies in real food systems require isolation of the target organism from the surrounding environment to ensure that signal-to-noise ratios are sufficiently large to observe. Often, a technique known as immunomagnetic separation (IMS) is used to satisfy this requirement. IMS uses magnetic particles attached to selective antibodies in combination with a magnet to selectively separate the target analyte from the food matrix prior to detection. Nanoscale magnetic particles are especially useful in this regard due to their extremely high surface-to-volume ratios, which facilitate large analyte capture efficiencies. Captured analytes can then be easily purified and subjected to standard measurement techniques. This approach is illustrated graphically in Fig. 5.

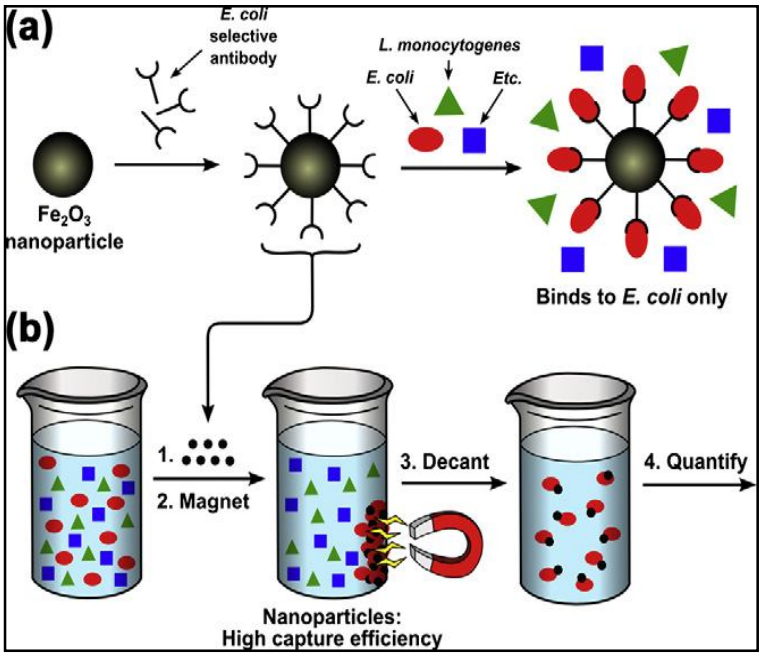

Figure 5: Schematic illustrating IMS-based detection methods using magnetic nanoparticles. (a) Antibodies selective for specific bacterial strains or species (e.g., E. coli) are bound to the surfaces of magnetic nanoparticles (e.g., Fe_2O_3). Only the targeted organisms will bind to the functionalized magnetic nanoparticles. (b) A complex matrix (e.g., food, blood, milk, etc.) contains the target analyte as well as numerous potential interferences, such as other bacterial species, viruses, proteins, food or blood particles, etc. Functionalized magnetic nanoparticles are added to the matrix, where they bind selectively and with high capture efficiency to the target analyte. A magnetic field isolates the analyte-bound magnetic particles, after which the supernatant is then carefully decanted. The remaining material is then subjected to quantification assays. In more sophisticated systems, the magnetic nanoparticles themselves are the means of detection and quantification (Adapted from: Duncan, 2011)

For instance, attachment of antibodies selective for *L. monocytogenes* onto functionalized, magnetic iron oxide nanoparticles can be used to efficiently separate the target bacteria from artificially contaminated milk and detect them using realtime PCR analysis (Yang *et al*., 2007). A similar approach has been used to isolate *E. coli* from freshly ground beef with >94% capture efficiency and no interference from other tested bacterial species (Varshney *et al*., 2005). Magnetic nanoparticles can be used to isolate *Mycobacterium avium spp. paratuberculosis* from contaminated whole milk and determine the bacterial concentration by observing effects of conjugation-induced magnetic particle agglomeration on the spin–spin (T2) relaxation times of nearby water protons (Kaittanis *et al*., 2007); importantly, this method is not susceptible to interference from other bacterial species that may be present in the matrix.

3. Electrochemical Nanosensors

Electrochemical nanosensors operate by binding selective antibodies to a conductive nanomaterial (e.g., carbon nanotube) and then monitoring changes to the material's conductivity when the target analyte binds to the antibodies. For example, conduction changes which occur when Microcystin-LR (MCLR), a toxin produced by cyanobacteria, binds to the surface of anti-MCLR-coated single-walled carbon nanotubes are easily detectable down to MCLR concentrations of 0.6 nM, which easily satisfies the guidelines set by World Health Organization for this substance in drinking water (Wang *et al*., 2009). This technique improves the sampling time over traditional MCLR measurement methods (e.g., ELISA) by an order of magnitude. A similar strategy utilizing AuNPs and glucose-sensitive enzymes can be used to measure glucose concentrations in commercial beverages (Ozdemir *et al*., 2010). A reusable piezoelectric AuNP immunosensor has been developed which detects the presence of aflatoxin-B17 in contaminated milk samples down to a concentration of 0.01 ng/mL (Jin *et al*., 2009).

Electrochemical detection might be based on the nanomaterials like nanowire, carbon nanotube or nanocantilever.

3.1. Nanowire-Based Electrochemical Detection

Nanomaterials lend themselves well to multiplexing assays, as in the case of a barcode-style method which utilizes binding of selective antibodies to specific regions of magnetic (and nonmagnetic) multi-metal nanowires for the simultaneous, multiplexed optical detection of bacteria, viruses and protein- based toxins.

Wang *et al*. (2009) fabricated conductive TiO_2 nanowire bundles, coated them with antibodies selective for *L. monocytogenes*, and deposited them between two gold electrodes, as shown in Fig. 6. In contaminated samples, bacteria bind to the antibodies, which cause a measurable change in impedance across the nanowire bundle. Using this technique, the authors were able to detect as low as 4.7×10^2 CFU/mL *L. monocytogenes* in 1 h without significant interference from other food-borne pathogens; this is a significant improvement over traditional Immuno-Dot Blot analysis, which had a detection limit of 2.2×10^5 CFU/mL.

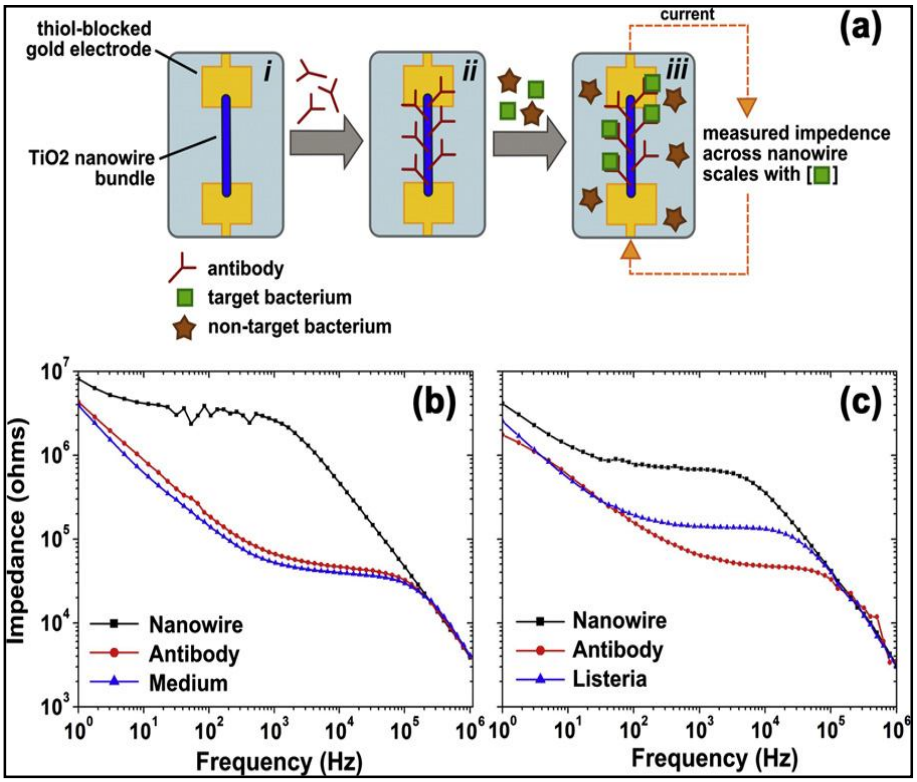

Figure 6: Impedance based detection of bacteria. (a) Gold electrodes protected with n-butylthiol ligands are connected with a conductive TiO_2 nanowire bundle. Antibodies selective to the target bacterium are then bound to the nanowire bundle. When the sensor is exposed to a complex matrix containing the target organism, changes in the electrical (impedance) properties of the bundle due to bacterium-antibody binding events can be readily observed. (b) and (c) Sample data set illustrating the detection of Listeria monocytogenes at a concentration of 4.65×10^3 cfu/ml. Note that exposure to a control medium (b) causes no changes to the impedance across the bundle, but that exposure to the bacteria (c) results in easily observable impedance changes due to immunoselective binding events (Adapted from: Wang et al., 2009)

Changes in conductance or resistance across circuits manufactured from or including nanoscale components have also been used to detect members of the Bacillus (Pal *et al*., 2007), Salmonella (Villamizar *et al*., 2008; de la Rica *et al*., 2008), and Escherichia (Lin *et al*., 2008; So *et al*., 2008) bacterial genera, as well as viruses (de la Rica *et al*., 2008).

3.2. Carbon Nanotube-Based Electrochemical Detection

Carbon nanotube consist of concentric cylinders a few nanometres in diameter and up to hundreds of micrometres in length. Carbon nanotube (CNT) based electrochemical detections have found good applications in the food analysis. CNT-based electrochemical detection in microfluidic devices can be used to measure antioxidant, flavour compound and vitamin content in vanilla beans and apples (Crevillen *et al*., 2007). Other electrochemical nanosensing systems based on carbon nanotubes include: an immunosensor based on a cerium oxide nanoparticle and chitosan nanocomposite which detects staphylococcal enterotoxin B (Mishra *et al*., 2008) and cholera-toxin (Viswanathan *et al*., 2006).

3.3. Nanocantilever-Based Electrochemical Detection

Nanocantilevers are another innovative class of nanosensors. Their detection principle is based on their ability to detect biological-binding interactions, such as between antigen and antibody, enzyme and substrate or cofactor and receptor and ligand, through physical and/or electrochemical signaling (Hall *et al*., 2002). They consist of tiny pieces of silicon-based materials that have the capability of recognizing proteins and detecting pathogenic bacteria and viruses (Kumar, 2006). Nanocantilever devices have already had tremendous success in studies of molecular interactions and in the detection of contaminant chemicals, toxins and antibiotic residues in food products (Ramirez Frometa, 2006).

Pathogen detection is based on their ability to vibrate at various frequencies in dependence on the biomass of the pathogenic organisms. The silicon surface of nanocantilevers can be modified to attach antibodies, resulting in a change of the resonant frequency depending on the attached mass. Gfeller *et al*. (2005) were able to detect *Escherichia coli*, which is an indicator of faecal pollution of water and food products, with the help of a cantilever coated with agarose (Fig. 7).

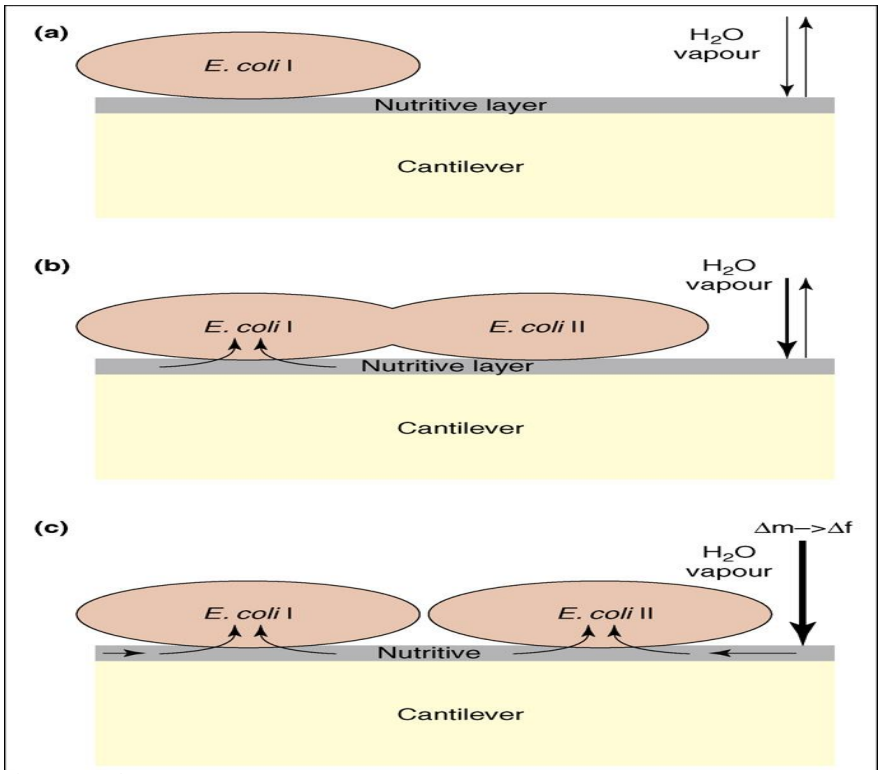

Figure 7: Illustration of the function of a nanocantilever sensor that is based on mass increase due to bacterial growth. (a) E. coli cells are deposited on top of an agarose-coated cantilever. The thin nutritive layer (~200 nm thick) stays in equilibrium with the humid environment. (b) The bacteria start to grow and assimilate water, protein, salts and carbohydrates from the nutritive layer. (c) To regain equilibrium with the humid environment, the nutritive layer absorbs water. This compensation leads to additional mass load (Dm refers to change in mass load) onto the cantilever that can be sensed by the change in frequency levels (Df) from the cantilever (Adapted from: Gfeller et al., 2005)

4. Optical Nanosensors

Optical techniques are more commonly employed for pathogen detections and they are based on fluorescence and Surface Plasmon Resonance (SPR). These techniques generally rely on monitoring the change of the optical signal that occurs between a functionalized nanomaterial and a pathogen. The main advantage of this type of sensors is that they can be introduced into the deeper part of cells with minimal physical perturbation of the cell. Nanomaterials such as Au NPs, gold NRs, Fe_3O_4 NPs and QDs have very good optical properties which do them excellent optical labels for improving the sensitivity of optical transducer surfaces of nanosensors. Optical transducers are particularly attractive for developing robust devices, easy to use, portables, and if possible with an inexpensive analytical system.

4.1. Fluorescence Based Nanosensors

Here the sensitivity of fluorescence is utilized for making quantitative measurements in the intracellular environment. A study has been carried out for *E. coli* detection using epifluorescent microscopy (El-Boubbou *et al*., 2007). This method consisted of functionalizing the surface of MNPs with D-manosse sugar (man-MNPs) through an amide linkage, subsequently incubations with fluorescein-labeled concanavalin A (Con A) at 4^0C for 12 h and incubations with *E. coli* cells (10^3-10^7 cells/mL, 1 mL) in PBS buffer. After incubating MNPs with solutions of *E. coli* for a few minutes, a magnetic field was applied separating MNPs/*E. coli* aggregates (Fig. 8 (a)). The supernatants were removed and the remaining aggregates were washed thoroughly, stained with a fluoresecent dye (PicoGreen), transferred to a glass slide, and imaged. Fluorescent microscopic imaging showed that *E. coli* can be detected (Fig. 8(b)) with a limit of detection 10^4 cells/mL.

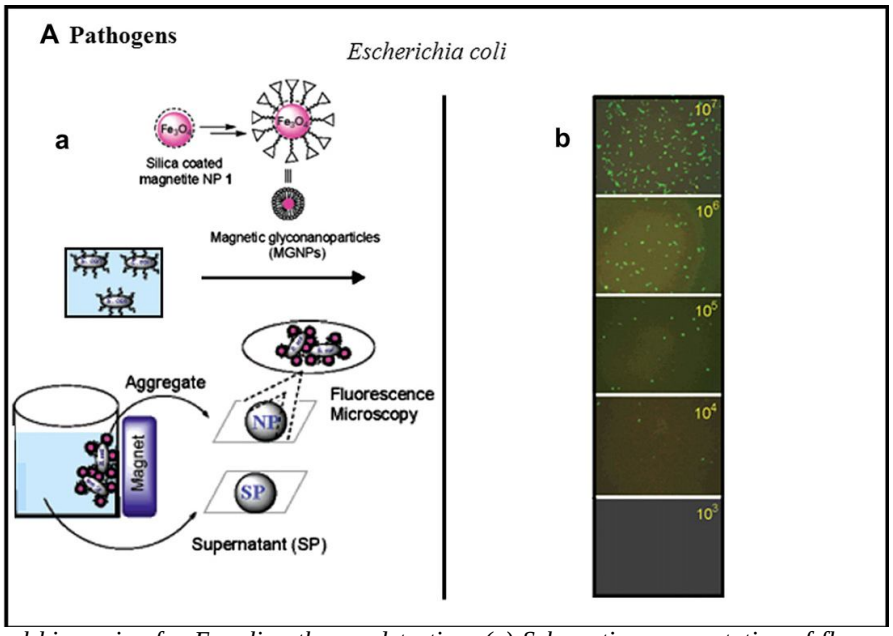

Figure 8: Example of optical biosensing for E. coli pathogen detection. (a) Schematic representation of fluorescent sensing of the E. coli pathogen based on the functionalization of the silica coated magnetite nanoparticles. (b) Increase in the fluorescent emmision spectra for increasing concentrations (cells/mL) of E. coli.

4.2. Plasmonics Based Nanosensors

Some types of optical sensors are based on Surface Plasmon Resonance (SPR). The term plasmonics is derived from "plasmons", which are the quanta associated with longitudinal waves propagating in matter through the collective motion of large numbers of electrons. Incident light irradiating these surfaces excites conduction electrons in the metal, and induces excitation of surface plasmons leading to enormous electromagnetic enhancement for ultrasensitive detection of spectral signatures: Surface-Enhanced Raman Scattering (SERS) and Surface-Enhanced Fluorescence (SEF).

Like infrared spectroscopy, Raman spectroscopy is a particularly valuable tool for the identification and detection or organic compounds because each molecule has a unique pattern of molecular vibrations which gives rise to a correspondingly unique spectral fingerprint. Surface-Enhanced Raman Scattering (SERS) effect is caused by interaction of molecular electronic states with localized electric fields generated by photoexcitation of metal surface plasmons. Because of orientation requirements between the molecular transitions and the Plasmon oscillations, SERS enhancement is greatest on surfaces with large degrees of curvature or ''roughness''. As a result, nanoscale metal structures, such as those comprised of gold or silver, give rise to the most enhanced, and thus practically useful, SERS signals for characterization and detection of analytes.

SERS using nanoscale substrates has proven to be a useful platform for the detection of food-related analytes. For instance, Mengshi Lin and co-workers have pioneered the use of fractal-like or patterned gold nanostructures as substrates to detect compounds of interest to food safety, including melamine and its derivatives, as well as crystal violet (Fig. 9) and malachite green (0.2 ppb level) (He *et al*., 2008a), which are two FDA-banned fungicides/ antimicrobials often found in fish grown in contaminated waters.

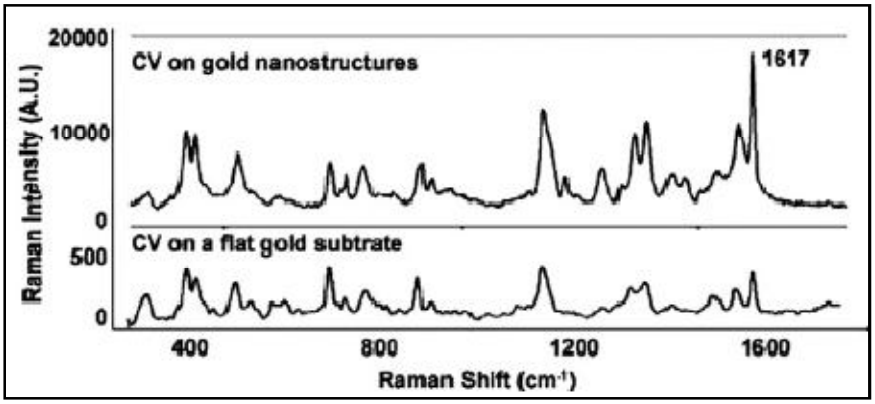

Figure 9: SERS spectrum of 2 ppb crystal violet (CV) on gold nanostructures and a ''normal'' Raman spectrum of 2000 ppm CV on the control (a gold-coated glass slide). Both spectra were acquired under identical Raman instrumental conditions. Note that the spectral intensity for CV on the SERS substrate is effectively 4 x10^7 times larger than that of the conventional Raman experiment. Because each chemical compound exhibits a different spectral fingerprint, SERS can be used to quickly and accurately detect a wide range of food contaminants, including living organisms.

SERS-based detection method might be useful for quick screening of food samples, followed by conventional HPLC analysis for the elimination of false positives.

In addition to chemical contaminants, SERS can also be used to detect and identify food-borne pathogens, as each bacterial species appears to have a unique fingerprint arrangement of spectral peaks. For instance, single Bacillus spores can be detected using SERS and nanostructured gold substrates, and several different Bacillus species can be easily distinguished (He *et al*., 2008b). Silver substrates can be used to rapidly and simultaneously screen for *E. coli*, *L. monocytogenes*, and *S. typhimurium* (Yang *et al*., 2008). In a more recent report a research group has also used a combination of magnetic separation with labeled silica-coated magnetic nanoparticles and AuNPs labeled with Raman reporter molecules for multiplexed SERS detection of *S. enterica serovar typhimurium* and *S. aureus* in spinach wash and peanut butter emulsion with a detection limit of 10^3 CFUs/mL (Wang *et al*., 2011).

4.3. Futuristic Grain Quality Monitoring Nanosensors

Grain quality monitoring nanosensors (Fig. 10), are being developed by researchers at the Canadian Wheat Board Centre for Grain Storage Research, University of Manitoba, Canada. They use conducting polymer nanoparticles (Neethirajan *et al*., 2009), which respond to analytes and volatiles in the food storage environment and thereby detect the source and the type of spoilage.

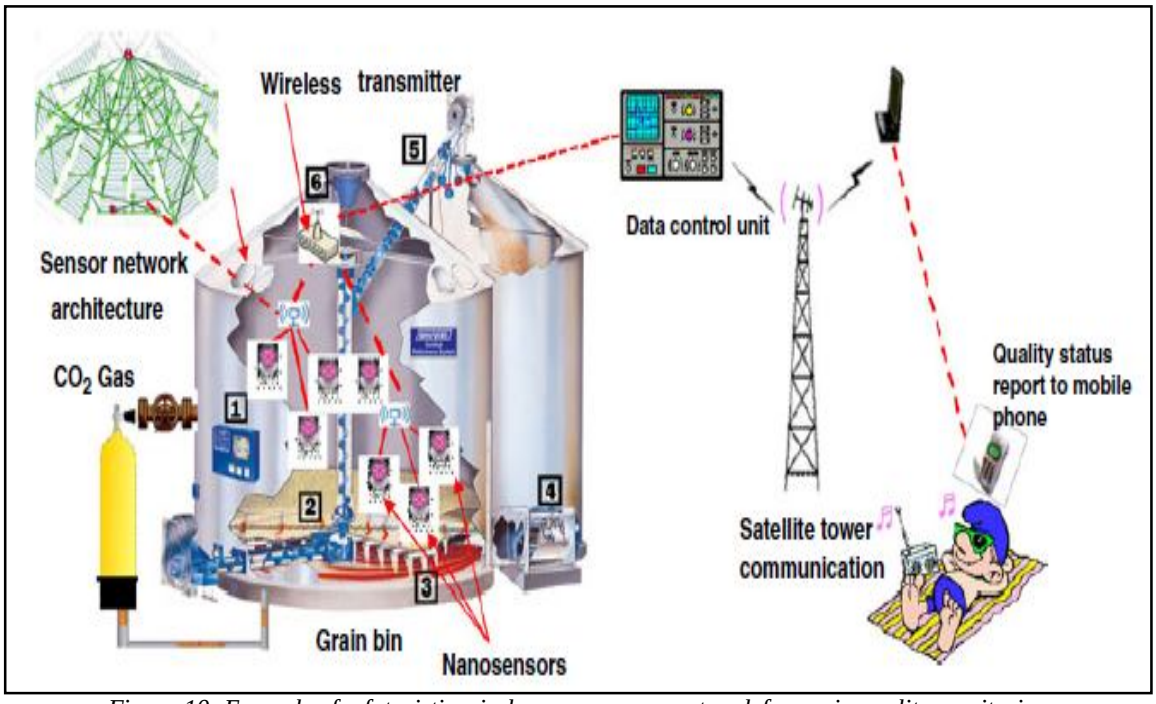

Figure 10: Example of a futuristic wireless nanosensor network for grain quality monitoring

1 Control panel, 2 grain auger, 3 air plenum, 4 fan, 5 auger to transfer grain, if needed,
6 wireless transmitter (Neethirajan *et al*., 2009)

The advantage of this sensor system is that thousands of nanoparticles can be placed on a single sensor to accurately detect the presence of insects or fungus inside stored grain bulk in bins. Because of the miniaturization and low power requirement, the nanosensors can be fabricated small and light weight (Neethirajan & Jayas, 2007) and can be deployed and distributed into the crevices of grain bulk, where the stored product pests often hide.

5. Conclusion

In the food sector, one of the most important problems is the time-consuming and laborious process of food quality analysis. Innovative devices like nanosensors are being developed to facilitate precise and inexpensive analysis of foods. They can detect microorganisms or chemical contaminants at surprisingly low levels. This review has discussed in detail the most promising applications of nanosensors for food analysis and the techniques by which the nanosensors are used. Some companies (e.g., Ripesense [http://www.ripesense.com] and OnVu [http://www.onvu.com/]) already market nanosensor based products that help consumers determine whether certain foods are likely to be palatable, but most of the work on nanosensors for food analysis is still in the early stages of development. Further research and commercialisation of this technology would obviously benefit consumers, industry stakeholders and food regulators.

6. References

i. Ai, K., Liu, Y., & Lu, L. (2009). Hydrogen-bonding recognition-induced color change of gold nanoparticles for visual detection of melamine in raw milk and infant formula. Journal of the American Chemical Society, 131(27), 9496-9497.
ii. Arndt, G.W. (2008). Leak testing, in: K.L. Yam (Ed.), The Wiley Encyclopedia of Packaging Technology, third ed., John Wiley and Sons, Inc., New York.
iii. Bouwmeester, H., Dekkers, S., Noordam, M. Y., Hagens, W. I., Bulder, A. S., De Heer, C., ... & Sips, A. J. (2009). Review of health safety aspects of nanotechnologies in food production. Regulatory toxicology and pharmacology,53(1), 52-62.

iv. Bultzingslowen, C.V., McEvoy, A.K., McDonagh, C., MacCraith, B.D., Klimant, I., Krause, C., Wolfbeis, O.S. (2002). Sol–gel based optical carbon dioxide sensor employing dual luminophore referencing for application in food packaging technology. Analyst, 127, 1478–1483.

v. Chen, J. R., Miao, Y. Q., He, N. Y., Wu, X. H., & Li, S. J. (2004). Nanotechnology and biosensors. Biotechnology Advances, 22(7), 505–518.

vi. Crevillén, A. G., Ávila, M., Pumera, M., González, M. C., & Escarpa, A. (2007). Food analysis on microfluidic devices using ultrasensitive carbon nanotubes detectors. Analytical chemistry, 79(19), 7408-7415.

vii. de la Rica, R., Mendoza, E., Lechuga, L. M., & Matsui, H. (2008). Label-Free Pathogen Detection with Sensor Chips Assembled from Peptide Nanotubes.Angewandte Chemie International Edition, 47(50), 9752-9755.

viii. Duncan, T.V. (2011). Applications of nanotechnology in food packaging and food safety: Barrier materials, antimicrobials and sensors. Journal of Colloid and Interface Science 363, 1–24.

ix. El-Boubbou, K., Gruden, C., & Huang, X. (2007). Magnetic Glyconanoparticles: a unique tool for rapid pathogen detection, decontamination, and strain differentiation. Journal of the American Chemical Society, 129, 13392-13393.

x. Esposito, E. et al. (2005) Cubosome dispersions as delivery systems for percutaneuos administration of indomethacin. Pharm. Res. 22, 2163– 2173

xi. German, J. B., Smilowitz, J. T., & Zivkovic, A. M. (2006). Lipoproteins: When size really matters. Current opinion in colloid & interface science, 11(2), 171-183.

xii. Gfeller, K.Y. et al. (2005) Micromechanical oscillators as rapid biosensor for the detection of active growth of Escherichia coli. Biosens. Bioelectron. 21, 528–533

xiii. Goldman, E. R., Clapp, A. R., Anderson, G. P., Uyeda, H. T., Mauro, J. M., Medintz, I. L., & Mattoussi, H. (2004). Multiplexed toxin analysis using four colors of quantum dot fluororeagents. Analytical Chemistry, 76(3), 684-688.

xiv. Hall, R.H. (2002) Biosensor technologies for detecting microbiological food borne hazards. Microbes Infect. 4, 425–432.

xv. Haruyama, T. (2003). Micro- and nanobiotechnology for biosensing cellular responses. Advanced Drug Delivery Reviews, 55(3), 393–401.

xvi. He, L., Kim, N. J., Li, H., Hu, Z., & Lin, M. (2008a). Use of a fractal-like gold nanostructure in surface-enhanced Raman spectroscopy for detection of selected food contaminants. Journal of agricultural and food chemistry, 56(21), 9843-9847.

xvii. He, L., Liu, Y., Lin, M., Mustafa, A., Wang, Y. (2008b). Detecting singleBacillusspores by surface enhanced Raman spectroscopy. Sens. Instrum. Food Qual. 2 (4), 247-53.

xviii. Hernandez-Jover, T., Izquierdo-Pulido, M., Veciana-Nogués, M. T., Mariné-Font, A., & Vidal-Carou, M. C. (1997). Biogenic amine and polyamine contents in meat and meat products. Journal of Agricultural and Food Chemistry, 45(6), 2098-2102.

xix. Jain, K. K. (2003). Nanodiagnostics: Application of nanotechnology in molecular diagnostics. Expert Review of Molecular Diagnostics, 3(2), 153–161.

xx. Jin, R. C., Wu, G. S., Li, Z., Mirkin, C. A., & Schatz, G. C. (2003). What controls the melting properties of DNA-linked gold nanoparticle assemblies? Journal of the American Chemical Society, 125(6), 1643–1654.

xxi. Jin, X., Jin, X., Chen, L., Jiang, J., Shen, G., & Yu, R. (2009). Piezoelectric immunosensor with gold nanoparticles enhanced competitive immunoreaction technique for quantification of aflatoxin B 1. Biosensors and Bioelectronics,24(8), 2580-2585.

xxii. Kaittanis, C., Naser, S. A., & Perez, J. M. (2007). One-step, nanoparticle-mediated bacterial detection with magnetic relaxation. Nano letters, 7(2), 380-383.

xxiii. Kumar, C. S. S. R. Nanomaterials for biosensors. Nanotechnologies for the life sciences (2006), 8. Wiley-VCH Weinheim.

xxiv. Lee, S. K., Mills, A., & Lepre, A. (2004). An intelligence ink for oxygen.Chemical communications, (17), 1912-1913.

xxv. Lee, S. K., Sheridan, M., & Mills, A. (2005). Novel UV-activated colorimetric oxygen indicator. Chemistry of Materials, 17(10), 2744-2751.

xxvi. Ligler, F.S. et al. (2003) Array biosensor for detection of toxins. Anal. Bioanal. Chem. 377, 469–477

xxvii. Lin, Y. H., Chen, S. H., Chuang, Y. C., Lu, Y. C., Shen, T. Y., Chang, C. A., & Lin, C. S. (2008). Disposable amperometric immunosensing strips fabricated by Au nanoparticles-modified screen-printed carbon electrodes for the detection of foodborne pathogen Escherichia coli O157: H7. Biosensors and Bioelectronics,23(12), 1832-1837.

xxviii. Liu, Y., Ai, K., Cheng, X., Huo, L., & Lu, L. (2010). Gold-Nanocluster-Based Fluorescent Sensors for Highly Sensitive and Selective Detection of Cyanide in Water. Advanced Functional Materials, 20(6), 951-956.

xxix. Luechinger, N. A., Loher, S., Athanassiou, E. K., Grass, R. N., & Stark, W. J. (2007). Highly sensitive optical detection of humidity on polymer/metal nanoparticle hybrid films. Langmuir, 23(6), 3473-3477.

xxx. Mills, A. (2005). Oxygen indicators and intelligent inks for packaging food.Chemical Society Reviews, 34(12), 1003-1011.

xxxi. Mills, A., & Hazafy, D. (2009). Nanocrystalline SnO 2-based, UVB-activated, colourimetric oxygen indicator. Sensors and Actuators B: Chemical, 136(2), 344-349.

xxxii. Mishra, N. N., Maki, W. C., Cameron, E., Nelson, R., Winterrowd, P., Rastogi, S. K., ... & Maki, G. K. (2008). Ultra-sensitive detection of bacterial toxin with silicon nanowire transistor. Lab on a Chip, 8(6), 868-871.

xxxiii. Nath, N., & Chilkoti, A. (2004a). Label-free biosensing by surface plasmon resonance of nanoparticles on glass: Optimization of nanoparticle size. Analytical Chemistry, 76(18), 5370–5378.

xxxiv. Nath, N., & Chilkoti, A. (2004b). Label free colorimetric biosensing using nanoparticles. Journal of Fluorescence, 14(4), 377–389.

xxxv. Neethirajan, S., & Jayas, D. S. (2007). Sensors for grain storage. In: ASABE Annual International Meeting, 17-20 June 2007, Minneapolis, USA.

xxxvi. Neethirajan, S., Freund, M. S., Shafai, C., Jayas, D. S., & Thomson, D. J. (2009). Development of carbon dioxide sensor for agri-food industry. United States Provisional Patent No. 2009-61/23891 (in English).

xxxvii. Ozdemir, C., Yeni, F., Odaci, D., & Timur, S. (2010). Electrochemical glucose biosensing by pyranose oxidase immobilized in gold nanoparticle-polyaniline/AgCl/gelatin nanocomposite matrix. Food chemistry, 119(1), 380-385.

xxxviii. Pal, S., Alocilja, E. C., & Downes, F. P. (2007). Nanowire labeled direct-charge transfer biosensor for detecting Bacillus species. Biosensors and Bioelectronics, 22(9), 2329-2336.

xxxix. Pimtong-Ngam, Y., Jiemsirilers, S., & Supothina, S. (2007). Preparation of tungsten oxide–tin oxide nanocomposites and their ethylene sensing characteristics. Sensors and Actuators A: Physical, 139(1), 7-11.

xl. Ramirez Frometa, N. (2006) Cantilever biosensors. Biotecnol. Apl. 23, 320–323

xli. Ritter, S.K. (2005) An eye on food. Chem. Eng. News 83, 28–34

xlii. Sanguansri, P. & Augustin, M.A. (2006) Nanoscale materials development- a food industry perspective. Trends Food Sci. Technol. 17, 547–556

xliii. So, H. M., Park, D. W., Jeon, E. K., Kim, Y. H., Kim, B. S., Lee, C. K., ... & Lee, J. O. (2008). Detection and Titer Estimation of Escherichia coli Using Aptamer-Functionalized Single-Walled Carbon-Nanotube Field-Effect Transistors. Small, 4(2), 197-201.

xliv. Sozer, N and. Kokini, J.L. (2008). Nanotechnology and its applications in the food sector. Trends in Biotechnology, Vol.27 No.2. doi:10.1016/j.tibtech.2008.10.010.

xlv. Staiano, M., Matveeva, E. G., Rossi, M., Crescenzo, R., Gryczynski, Z., Gryczynski, I., ... & D'Auria, S. (2009). Nanostructured silver-based surfaces: new emergent methodologies for an easy detection of analytes. ACS applied materials & interfaces, 1(12), 2909-2916.

xlvi. USDA. (2003). Nanoscale Science and Engineering for Agriculture and Food Systems, Dept. of Agriculture, United States.

xlvii. Varshney, M., Yang, L., Su, X. L. & Li, Y. (2005). Magnetic nanoparticle–antibody conjugates for the separation of Escherichia coli O157:H7 in ground beef. J. Food. Prot.68, 1804–11.

xlviii. Villamizar, R. A., Maroto, A., Rius, F. X., Inza, I., & Figueras, M. J. (2008). Fast detection of Salmonella Infantis with carbon nanotube field effect transistors. Biosensors and Bioelectronics, 24(2), 279-283.

xlix. Viswanathan, S., Rani, C., Anand, A. V., & Ho, J. A. A. (2009). Disposable electrochemical immunosensor for carcinoembryonic antigen using ferrocene liposomes and MWCNT screen-printed electrode. Biosensors and Bioelectronics, 24(7), 1984-1989.

l. Vo-Dinh, T., Cullum, B. M., & Stokes, D. L. (2001). Nanosensors and biochips: Frontiers in biomolecular diagnostics. Sensors and Actuators, B: Chemical, 74(1–3), 2–11.

li. Wang, L., Chen, W., Xu, D., Shim, B. S., Zhu, Y., Sun, F., ... & Kotov, N. A. (2009). Simple, Rapid, Sensitive, and Versatile SWNT− Paper Sensor for Environmental Toxin Detection Competitive with ELISA. Nano letters, 9(12), 4147-4152.

lii. Wang, Y., Ravindranath, S., & Irudayaraj, J. (2011). Separation and detection of multiple pathogens in a food matrix by magnetic SERS nanoprobes.Analytical and bioanalytical chemistry, 399(3), 1271-1278.

liii. Yang, H., Li, H., & Jiang, X. (2008). Detection of foodborne pathogens using bioconjugated nanomaterials. Microfluidics and nanofluidics, 5(5), 571-583.

liv. Yang, H., Qu, L., Wimbrow, A. N., Jiang, X., & Sun, Y. (2007). Rapid detection of Listeria monocytogenes by nanoparticle-based immunomagnetic separation and real-time PCR. International Journal of Food Microbiology, 118(2), 132-138.

lv. Yih, T.C. and Al-Fandi, M. (2006) Engineered nanoparticles as precise drug delivery systems. J. Cell. Biochem. 97, 1184–1190