Chapter 10
Significance of Nanoscience in Food Microbiology: Current Trend and Future Prospects

Ajay Kumar, Amit Pratush, and Surojit Bera

Abstract Nanotechnology is an outstanding discovery for mankind which transform the food industry and conventional food science. Nanomaterial used in food sector could have different properties like solubility, thermodynamic, magnetic, optical, colour, etc. A nanostructure of a material widely differs from its macrostructure in terms of the texture, taste, odour, charge on the surface, etc. Nanosensing, nanostructured ingredients and packaging are the major areas where nanotechnology revolutionized the food industry. As compared to traditional practices, nanotechnology-based active and intelligent methods have greater advantages like increased mechanical strength, nanosensor for pathogen detection and improved gas exchange. The natural nanostructures are mostly proteins such as milk proteins like casein, polysaccharides, lipids, etc., whereas the synthetic nanostructures are polymeric NPs, nanoemulsions and liposomes. Several nanomaterials which control or pause chemical reactions lead to the spoilage used in the food industry for sustainable food characteristic preservation. Nanotechnology also works on a two-way approach to maintain or preserve food characteristics, i.e. modifying the packaging technology or changing the bioactivity of active food components in the packaging environment. However, there are some odds like safety issues creating challenges in modern nanotechnology. In the long run, proper training of the public is needed to ensure the benefits and safety of the application of nanotechnology in the food industry.

Keywords Nanomaterial · Active packaging · Encapsulation · Biosensor · Bioactive molecules

A. Kumar · S. Bera (✉)
Department of Microbiology, School of Bioengineering and Biosciences, Lovely Professional University, Phagwara, Punjab, India

A. Pratush
Arboreal Bio-Innovations Pvt. Ltd., Lucknow, Uttar Pradesh, India

N. R. Maddela et al. (eds.), *Nanotechnology for Advances in Medical Microbiology*, Environmental and Microbial Biotechnology,
https://doi.org/10.1007/978-981-15-9916-3_10

10.1 What is Nanoscience?

Nanoscience or nanotechnology is the functional area of modern era, where unification of science with engineering opens a new door in everyday science. In this area productive molecule size varies between 1 and 100 nanometre at least in one dimension. It is also the foundation and deployment of ingredients, manoeuvre or system, through the regulation of the properties and structure of the matter at the nanometric scale. However according to some researchers, there is a fine line between nanoscience and nanotechnology which distinguishes them between each other. For example, nanoscience is a junction physical science, chemical science, biological science and mathematics which deals with the fabrication of materials at the atomic and molecular level; on the other hand, nanotechnology is the measurement, congregation, control and manufacturing of matters at nanoscale. It is the most truly immerging technology of the twenty-first century. The concept of nanotechnology was first familiarized by a Nobel laureate Richard Feynman in 1959 (Bayda et al. 2020). He was an American physicist who showed the pathway towards this small but powerful field of study. Almost 15 years later, a Japanese scientist Norio Taniguchi first defined the term “nanotechnology” in 1974 as “nanotechnology mainly consists of the processing of separation, consolidation, and deformation of materials by one atom or one molecule”. Taniguchi was also considered the father of modern nanotechnology by many scientists. It would be very clear from an example of economic investment in United States (US). In 2015 financial year, US federal R&D investment was calculated approximately $20 billion, more than double that by the private sector. The revenues generated from nanoproducts is continuously increasing with over $200B in financial year 2012 in the United States alone and over $700B worldwide (Bhushan 2016).

Now, the main question comes into mind that why should we go for such small and complicated nanosystem? The answer is embedded in the physical and chemical properties of particles. Matters mostly remain in three states: solid, liquid and gas. Where we cut down the bulk structures of the materials into very small fractions like nanoscale, the regular physical, chemical and biological properties differ. For example, in nanoscale some materials may act stronger, or lighter, and may have magnetic properties, better electricity or heat transfer. Also, they may become more chemically responsive or redirect light better or alter colour as their size or structure is altered. Figure 10.1 shows different aspects of nanoscience in food sectors and their ongoing applications.

10.2 Relation of Food Microbiology with Nanoscience

The topic we are discussing here is related to food microbiology also; and the food microbiology comes under the category of food science. The consumer’s preference about food colour, texture and overall quality is continuously changing with a

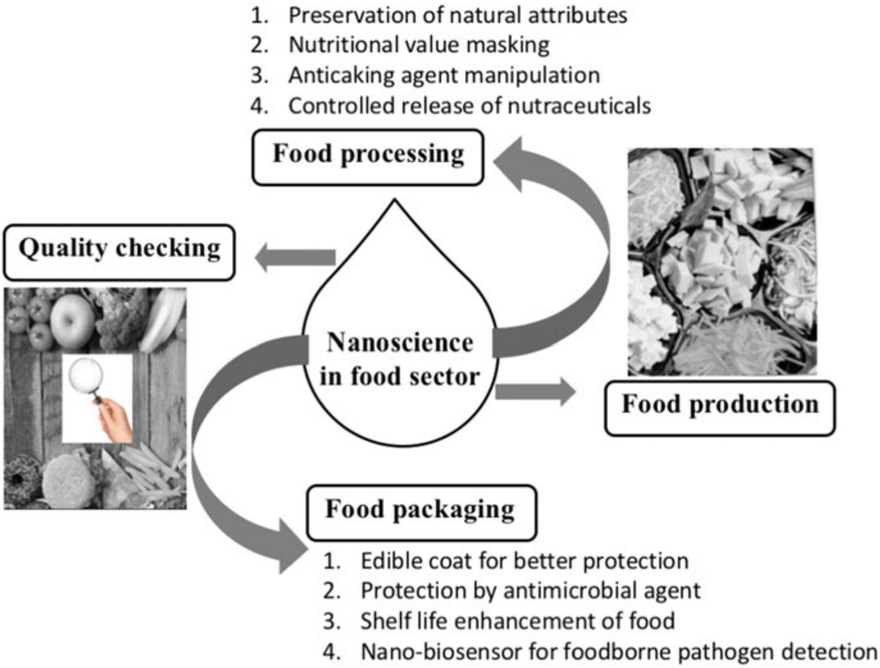

Fig. 10.1 Different aspect-cum-applications of nanoscience in food sector

growing concern over health benefits (Singh 2017). Now, consumers are also aware about the nutritional value of the product; and this nutritional value mostly depends upon various micronutrients and bioactive compounds. However, when microorganisms invaded the intactness of a food, their metabolic activities negatively amend these micronutrients and/or bioactive compounds jeopardizing the health benefits of the foods. As a result, researchers are continuously engaged in searching of new methods to improve the quality of foods without disturbing the basic contents of it.

In the immediate twentieth century, unceasing findings were made to comprehend the connection and significance of microorganisms, particularly pathogenic bacteria in food. Later but before the 1970s, the section food microbiology was considered as a functional science discipline which predominantly involved in the microbial quality control in food. Gradually with time, the technology expended in food manufacture, processing and food consumption patterns has considerably transformed. As a result, complications associated with it have also evolved vividly. These kinds of problems can no longer be solved by only technology application. Hence, research in basic food science and in modern food microbiology is inevitable to understand and effectually resolve the microbiological issues associated with food. The food microbiology discipline not only embraces microbiological aspects of food decomposition, food-borne infections and their efficient control but also fundamental evidence of microbial ecology, physiology, metabolism and genetics. An example of such application gained from food microbiology knowledge is genetically modified bacterial strains to produce fermented foods of better quality. However, emerging nanotechnology shows some prospects in this regard to conglomerate numerous regulatory procedures for effective control of food spoilage and pathogenic microorganisms in food.

Frequent investigation has been conducted to obtain human perception towards nanotechnology in the United States and in Europe. However, the data showed that community knowledge about nanotechnology is extremely narrow (Dingman JS 2008). According to the US Department of Agriculture (USDA), by 2015 the worldwide impression of products in the field of nanotechnology plays a crucial character, and it will be roughly $1 trillion yearly. Food microbiologists are attentive in quality control and quality assurance programs to fabricate innocuous and high-quality food products with zero defects and free of pathogens. In this chapter, we have discussed some key applications of nanotechnology in food microbiology in terms of food safety and human health. The chapter deals with application of nanotechnology in active packaging as antimicrobial agents (e.g. nanocomposite cellulose, etc.); food pathogen detection (e.g. through nanosensors); protection of "good" microbes (e.g. probiotics); food characteristic preservation (e.g. colour, texture, aroma, etc.), i.e. quality attributes; and their future applications.

10.3 General Applications of Nanoscience in Food Technology

Nanotechnology is an excellent technology which revolutionizes the food industry and conventional food science. Nanotechnology proved to be a great tool for the processing and packaging of various foods (Weiss et al. 2006). Nanoparticles used in food could be generated by different technologies which have different properties like solubility, thermodynamic, magnetic, optical, colour, etc. (Feng et al. 2010; Gupta et al. 2016). But till far the acceptability by the public and the agreement on rules for this technology worldwide are not clear (Bieberstein et al. 2013).

Nanotechnology improves the texture and taste, hides bad odour/taste and amends the size of the particle as well as charge on the surface (Powers et al. 2006). Increasing awareness and concern regarding health, nowadays consumers are very much particular about the quality of food and food safety. This necessitates the scientist to look for technology which strengthens the food safety without degrading the nutritional quality of food/product. As nontoxic nanomaterials sometimes contain essential elements and can withstant high pressure and temperature, the demand of these nanoparticles in food industry is very high (Sawai 2003).

The nanoscale development of around 5 nm edible nano-coating from nanoemulsion is used in various foods like bakery goods, vegetables, fruits, meat, fast foods, confectionary, etc. which act as a barrier for moisture and exchange of gases. This edible coating also serves as medium to deliver enzymes, colours, anti-browning compounds, antioxidants and flavour. The shelf life of opened manufactured food is also increased by edible coating (Azeredo et al. 2009; Naoto et al. 2009; Saxena et al. 2017; Nile et al. 2020).

Food nanosensing and food nanostructured ingredients are two major areas where nanotechnology has application in the food industry. Further, food nanostructured ingredients are related to food processing to food packaging, whereas food nanosensing are concerned with food safety and quality. Nanostructures applied in food processing used as antimicrobial agent, nutrient delivery carrier, improve durability and strength of packaging material, food safety, etc. (Ezhilarasi et al. 2013; Prasad et al. 2014, 2017a,b; Thangadurai et al. 2020).

It has been reported that food nanostructured ingredients improve consistency, texture and taste of food along with improvement in shelf life of food (Pradhan et al. 2015; Singh et al. 2017). Nanocarriers are used to deliver food additives without any adverse effect on the morphology of the food. The size of nanocarriers directly related to the absorption efficiency of the material in humans, i.e. if smaller the size, efficiently it is absorbed inside the host (Ezhilarasi et al. 2013; Singh et al. 2017). The following properties should be possessed by the ideal nanocarrier: (i) it must deliver active compound at a specific rate and at a specific time, (ii) it should be able to deliver active compound at a specific target site, and (iii) it must maintain active compound for longer period of time without any modification. The formation of biopolymer matrices, encapsulation, simple solution and emulsion can be done by the application of nanotechnology. The release efficiency and encapsulation properties of nanoparticles are better as compared to other systems. The encapsulation by the nanoparticles has shown excellent results like it has good control over the release of active compounds; it removes/captures odours or taste in food; with other compounds in food, it showed excellent compatibility; and during storage, processing and utilizing, it protects from chemicals, heat, moisture and biological degradation; and finally it also has an outstanding control over the availability of active agent at a target time and at a controlled rate (Weiss et al. 2006; Singh et al. 2017). Besides, the nanoparticles are very small in size so they are efficiently absorbed by the body and deliver the active compound at a target site (Singh et al. 2017).

Nanotechnology has an important role in improving food taste as well as improving the quality of food. The colour from juice of beetroot was removed using nanofilters without deteriorating the flavour. Also, for lactose-intolerant people, nanofilters were used to remove lactose from milk and substitute it with another sugar. Bioencapsulation of tomato with L-lactide improves the shelf life of tomato, and this can be used on other perishable foods to increase the shelf life (Yadav 2017; Nile et al. 2020). Nanofilters are also used to remove microbial contamination from water or milk (Sekhon 2010). The use of nanotechnology improves the photostability and thermal stability of recombinant soybean seed by encapsulating the molecules of cyanidin 3-O-beta-D-glucoside (anthocyanin, a plant pigment) which is present in the inner cavity of the seed (Zhang et al. 2014). Another important application of nanoencapsulation is for flavonoid rutin which has pharmacological activity, but due to less solubility, its use is limited in the food industry. The encapsulated rutin showed more solubility and improved stability (Yang et al.

2015; Singh et al. 2017). Nanomaterials of silicon dioxide and titanium dioxide are used in food as colour agents, and also these are used as flavour/fragrance carrier specially silicon dioxide (Dekkers et al. 2011). Vitamins, proteins, lipids, etc. are important bioactive molecules present in the food which are very sensitive to pH in the human stomach, and also they have less solubility. Encapsulation leads to the increased resistance to the adverse condition in the human body, and also it improves the solubility of these bioactive molecules which help in the increased assimilation. To efficiently deliver various important bioactive molecules using encapsulation method, different techniques are available like nanostructuration, nanoemulsion and nanocomposition. For example, vitamins and flavonoids are well encapsulated using polymeric nanoparticles which help in the efficiently transport and protection of these bioactive molecules (Langer and Peppas 2003). The bioactive molecules in the food get degraded due to the adverse conditions which may be inside the host or outside the host. The encapsulation of these bioactive molecules slows down the degradation rate and provides sufficient time to deliver these bioactive molecules at a target site. This encapsulation also acts as a carrier for the delivery of enzymes, flavour, antioxidant, colours, etc. and also prevents gas exchange or moisture absorption which improves the shelf life of even opened food (Renton 2006; Weiss et al. 2006; Singh et al. 2017). The encapsulation of curcumin which is the bioactive molecule present in turmeric leads to the increased stability of this molecule to ionic strength of various concentrations and also showed stability to pasteurization temperature (Sari et al. 2015; Singh et al. 2017).

10.4 Nanotechnology in Active Packaging of Food

Food packaging is an important part of food processing to improve shelf life. The ideal characteristic of packaging material includes strength, gas permeability and biodegradability (Couch et al. 2016; Singh et al. 2017). As compared to the methods of traditional packaging, nanotechnology-based “active” and “intelligent” methods have greater advantages like increased mechanical strength, nanosensor for pathogen detection and improved gas exchange (Mihindukulasuriya and Lim 2014; Singh et al. 2017). In the food industry, nanotechnology uses nanomaterials like nanoemulsions, nanoparticles and nanoclays to improve the shelf life of food. Nanocomposites are an important part of food packaging system. Many organic compounds (bacteriocins, essential oils, etc.) were tested by research workers as antimicrobial agents in polymeric matrices, but these organic compounds are susceptible to the various food processing steps like high temperature, etc. (Schirmer et al. 2009). So, these difficulties which are encountered during the use of organic compounds can be overcome by the use of nanoparticles (copper, iron, silver, zinc oxide, magnesium oxide, titanium oxide, etc.) which are stable under adverse conditions and even at low concentration showing powerful antimicrobial activities (Singh et al. 2017). Reactive oxygen species generated by titanium dioxide is highly lethal to microbes which make it as a suitable antimicrobial agent. The amendment of polymers with nanoparticles generates cost-effective strong packaging material. Nanocomposites used for coating and packaging purpose and their use improved the mechanical strength and heat resistance, generate low weight material and improve the gas/moisture exchange (Pinto et al. 2013; Mihindukulasuriya and Lim 2014). The amendment of polymeric matrix with active nanoparticles improves the thermal stability, decreases the permeability of gases, makes the matrix resistant to fire and generates light weight material (Duncan 2011). This amendment also improves the shelf life of food by providing scavenging, antimicrobial and antioxidant activity (Sorrentino et al. 2007). In packed food industries, the utilization of nanotechnology influences the aroma and flavour characteristic of food, growth of microbes and moisture regulation (Brody et al. 2008).

In the food industry, active and intelligent nanotechnology is widely used to improve the shelf life of various food products specially the packed one. In active packaging system, the incorporated component either absorbs moisture, oxygen and carbon dioxide or releases antioxidant or antimicrobial molecules either into the food or out of the food or in the vicinity of food environment which helps in the increase of shelf life of food. The quality and shelf life of food product improved by the blend of these active compounds with polymers (Ranjan et al. 2014; Majid et al. 2018). Many inorganic nanoparticles have important application in the food industry. The most common used inorganic nanoparticles are silver, iron, zinc, gold and oxides of metals like silicon oxide, titanium oxide, magnesium oxide, zinc oxide, etc. (Bikiaris and Triantafyllidis 2013). These nanoparticles either slowly migrate and react or directly react with organic molecule of food. These nanoparticles directly kill the microbes by damaging the cell envelop or by interfering the electron transport or indirectly by producing various reactive species or by oxidizing various components of cells (Li et al. 2008). Silver nanoparticles are most commonly used as an antimicrobial agent against most microbial strains. These silver nanoparticles are active not only against bacteria, but also they showed detrimental activity against fungi and viruses (Duncan 2011). These silver nanoparticles show bacteriostatic activity by binding to different proteins, enzymes and DNA of bacteria (Cavaliere et al. 2015; Aziz et al. 2014, 2015, 2016; Joshi et al. 2018).

Many researchers have successfully used silver nanoparticles to inhibit the persistence of common food-borne pathogens. The use of silver nanoparticles decreases the level of pathogenic *Clostridium perfringens* and *E. coli* in the animal feed which helps in the cut-down use of antibiotics in livestocks (Fondevila et al. 2009; Pineda et al. 2012; Elkloub et al. 2015; Adegbeye et al. 2019). Silver nanoparticles are also successfully used in the treatment of water by integrating these particles to filter (Zodrow et al. 2009; Dankovich and Gray 2011). In the food industry, the application of silver nanoparticles is still limited, but attempts are done to substitute the use of sulphur dioxide with these nanoparticles with antimicrobial activity specially in the wine industry (Izquierdo-Canas et al. 2012; Garde-Cerdan et al. 2014; Garcia-Ruiz et al. 2015). Many natural phytochemicals are used as antimicrobial agents in the packaging material for the food to improve the shelf life (Manso et al. 2013; Medina-Jaramillo et al. 2017; Moreno et al. 2019). But silver nanoparticles have greater antimicrobial activity as compared to these phytochemicals. The silver nanoparticles interact with food directly or with the polymer matrix. Stable nature of silver nanoparticles and slow release into the food make these nanoparticles an excellent option in the packaging of food (Duncan 2011). Various research workers used silver nanoparticles in combination with different polymers like laponite and cellulose nanofibrils (Wu et al. 2018; Yu et al. 2019) which showed a detrimental effect on *E. coli*, *S. aureus*, *L. monocytogenes*, *P. citrinum* and *A. niger*. The coating/covering of nanocomposite film (made of polyvinyl pyrrolidone along with silver nanoparticles) around the asparagus improved the shelf life at refrigerated temperature (An et al. 2008). A packaging film was prepared from banana powder, agar and silver nanoparticles that showed antibacterial activity against *L. monocytogenes* and *E. coli* (Orsuwan et al. 2016).

Besides silver, copper nanoparticles also showed promising antimicrobial activity results. These copper nanoparticles showed detrimental activity by degrading the DNA, enzymes, proteins, lipid peroxidation and production of reactive oxygen species (Chatterjee et al. 2014; Yadav et al. 2017). Cioffi et al. (2005) showed antimicrobial activity of copper nanoparticles against *S. aureus*, *E. coli*, *L. monocytogenes* and *S. cerevisiae*. Copper nanoparticles in polyurethane nanofibers showed excellent antibacterial activity against *B. subtilis* and *E. coli* (Sheikh et al. 2011). Besides this, various oxides of nanoparticles [silicon oxide (SiO_2), zinc oxide (ZnO), titanium dioxide (TiO_2) and magnesium oxide (MgO)] showed a promising result in food packaging. Silicon oxide nanoparticles showed improvement in barrier property and mechanical strength of the matrices of polymer. The silicon oxide amendment at the rate of 5% in nanocomposites showed enhancement in physical as well as mechanical properties (Salami-Kalajahi et al. 2012). The good amount of antibacterial activity is shown by zinc oxide nanoparticles. The zinc oxide nanoparticles produce reactive oxygen species which is detrimental to microbial cell, as well as it also produces zinc ions which have antimicrobial activity. Zinc oxide nanoparticles directly interact with the cell wall of the bacteria which leads to the lysis of bacterial cell (Sirelkhatim et al. 2015; Bhuyan et al. 2015). These zinc oxide nanoparticles are activated by visible light (Kim et al. 2020). Zinc ions generated from zinc oxide interact with respiratory enzymes in the bacterial cell and inhibit their activity. The absorption of zinc oxide nanoparticles in the bacterial cell ultimately damages DNA, mitochondria and cell membrane which leads to the formation of free radicals and reactive oxygen species. Because of all these events, oxidative stress is generated which hampers the activity of respiratory enzymes that cause the bacterial cell death (Kim et al. 2020). In a study it was found that different forms of zinc oxide nanoparticles (PVP-capped/coating, film, powder) in egg white and liquid culture media showed excellent antimicrobial activity against *Salmonella enteritidis* and *Listeria monocytogenes* (Jin et al. 2009). Petchwattana et al. (2016) in their study showed antibacterial activity of composite of zinc oxide and polybutylene succinate against *S. aureus* and *E. coli*.

Among all the oxides of nanoparticles, titanium oxide nanoparticles showed favourable and encouraging results (Farhoodi 2016; Sharma et al. 2017). These titanium oxide nanoparticles are activated only in the presence of ultraviolet light (Sharma et al. 2017). The activated titanium oxide nanoparticles interact with DNA, proteins and peptides of microbial cell which leads to the detrimental effect on microbial growth and eventually leads to the death (Brown et al. 2008; Sharma et al. 2017). The oxidative stress is generated by titanium oxide nanoparticles which strike on the cell membrane of bacteria; also hydroxyl radicals generated damage the bacterial DNA and modify enzyme activity which depends upon coenzyme A (Kubacka et al. 2014). In a study it was found that application of composite EVOH-titanium oxide nanoparticles after irradiation of 30 minutes showed 5-log reduction against tested pathogens (Cerrada et al. 2008). Recently, Azizi-Lalabadi et al. (2019) reported that titanium oxide nanoparticles in support into 4A zeolite decline the population of tested pathogenic bacterial species significantly.

10.5 Nanotechnology in Food Pathogen Detection

Food-borne diseases are caused by various biological agents like bacteria, fungi, viruses, etc. The conventional methods (microscopic method, immunological methods and nucleic acid methods) for the detection of pathogens are available, but they are complex, time-consuming, laborious, expensive reagents/equipment, and skilled manpower is required (Kaittanis et al. 2010) which leads to the delay in detection of toxin/pathogen and ultimately slows down the treatment process of infected host (Salyers and Whitt 2002; Manguiat and Fang 2013). Besides microbes, toxins produced by the microbes are also very detrimental to the human which damage the plasma membrane of the cell and may interfere with physiological activity (Salyers and Whitt 2002; Sonawane et al. 2014). The methods used for the detection of toxins also suffer from the same limitations which are encountered in the detection methods of microbes (Valdes et al. 2009; Lopez and Merkoci 2011; Salyers and Whitt 2002; Sonawane et al. 2014).

So, to overcome these problems/limitations, nanotechnology will play an important role with enhanced detection efficiency to detect toxins and microbial pathogens (Valdes et al. 2009; Lopez and Merkoci 2011; Kaittanis et al. 2010; Ali et al. 2011). In nanotechnology devices can be designed which can detect contaminant in shorter time, increase sensitivity and have other multifunctional roles (Jain 2005; Rosi and Mirkin 2005; Nath et al. 2008). Besides normal characteristic features possessed by the nanomaterial, they can be modified such a way that can be used for the detection of ligand which will be specific for each pathogen (Kaittanis et al. 2010; Jain 2005; Rosi and Mirkin 2005). The most common nanomaterial used in the detection of toxins and microbial pathogen includes magnetic nanoparticles, gold nanoparticles, silver nanoparticles, gold nanorods, quantum rods, etc. (Valdes et al. 2009; Lopez and Merkoci 2011).

Nanomaterial can be used to design a sensor that can detect food-borne pathogen/ toxins by sensing/detecting the volatile compounds, chemical transduction or specific biological entity (biosensor) (Singh et al. 2020). In biosensors receptor which is biological in nature recognizes the specific toxin/microbial cell which leads to the signal generation by various means like thermal, mass, optical or electrochemical processes. Most of the biosensors are based on changes in electric current or colours.

Heavy metals, microbial toxins and synthetic toxins (like pesticides) pose a great health risk to human population. Fungal toxins are extremely toxic even at a low level which is a challenge for the health sector. Mycotoxins reported generally contaminate around 25% of food grains worldwide. Mycotoxins' intoxication leads to cancer, kidney problem, vomiting and liver problem, and in severe cases, it leads to the death of the patient. *Penicillium verrucosum* and *Aspergillus ochraceus* are reported to produce one of the potent mycotoxin known as ochratoxin A. This toxin is highly toxic to human kidneys and reported to have immunotoxic and teratogenic effects (Petzinger and Ziegler 2000; Cheli et al. 2008; Hayat et al. 2012).

For the detection of ochratoxin A, the biosensor was developed using cerium oxide particles and single-stranded DNA aptamer which is specific for this toxin (Bulbul et al. 2016). The attachment of ochratoxin to the aptamer results into redox property changes in cerium oxide, and this will be quantified by the colour changes of tetramethylbenzidine. This biosensor is very sensitive even 0.15 nM ochratoxin can be detected by this biosensor.

The bacterial heat-stable toxin produced by *S. aureus* is known as staphylococcal enterotoxins which is associated with food-borne illness caused by the contaminated food consumption (Sonawane et al. 2014; Yang et al. 2008; Yang et al. 2009) which leads to vomiting, nausea, diarrhoea and anorexia (Sonawane et al. 2014). The current method of identification of this toxin is based on immunological methods like ELISA which are rapid but have less sensitivity. An optical biosensor was devised in which carbon nanotubes were immobilized with anti-staphylococcal enterotoxin antibodies which is further bounded to secondary antibody with attached horseradish peroxidase (Yang et al. 2008). The sensitivity of this biosensor is six to eight times more as compared to normal immunological sensors. Another important bacterial toxin is shiga-like toxin (stx) produced by the food-borne *E. coli* specially O157:H7 strain. For the detection of shiga-like toxin, a biosensor was prepared by using surface plasmon resonance assay. In this biosensor gold nanoparticles were attached with globotriose antigen which is highly specific to shiga-like toxin (Chien et al. 2008). Another toxin, brevetoxin, which is produced by *Karenia brevis* (marine dinoflagellate) is a possible contaminant in sea food. Brevetoxin is neurotoxic, and consumption leads to diarrhoea, loss of coordination, muscle pain, respiratory problems, paresthesia, etc. (Sonawane et al. 2014). A electrochemical immunosensor was developed to detect brevetoxin using gold nanoparticles attached with poly (amidoamine) which was bounded to conjugate of brevetoxin-bovine serum albumin with attached anti-brevetoxin antibodies with horseradish peroxidase (Tang et al. 2011). This biosensor showed high sensitivity to detect brevetoxin in the range of 0.03 to 8 ng/ml.

Besides toxin, the presence of pathogenic microorganisms in the contaminated food is a big challenge to the food industry. The conventional methods/techniques currently available to detect the presence of these food-borne pathogens are laborious, are time-consuming and required skilled personnel (de Boer and Beumer 1999). One of the common pathogenic strains of *E. coli* reported to be highly pathogenic is *E. coli* O157:H7 which is able to cause disease even if its 100 cells are present

(Sonawane et al. 2014). The infection of *E. coli* O157:H7 leads to symptoms like haemorrhagic colitis, cramps in the stomach, anaemia, haemolytic uremic syndrome, etc. (Sonawane et al. 2014). Through faecal matter contamination of food and water, this organism is able to cause outbreaks. For the detection of *E. coli* O157:H7, electrochemical immune sensor was devised using quantum dots of cadmium sulphide entrapped in the zeolitic imidazolate framework made of metal organic material (Zhong et al. 2019). In another study DNA-based sensor using single-stranded thiolated DNA probe specific to *eaeA* gene present in *E. coli* O157:H7 was used to develop quartz crystal microbalance sensor (Mao et al. 2006). Lin et al. (2008) devised biosensor for the detection of *E. coli* O157:H7 in milk. In this biosensor they used screen-printed carbon electrode on which double antibodies were fabricated using gold nanoparticles. The first antibody interacts with *E. coli* O157:H7, whereas the second antibody is attached to horseradish peroxidase enzyme. Another important food-borne pathogen in the food industry is *Salmonella*. The infection caused by this microbe causes a disease known as salmonellosis. The infection symptoms include diarrhoea, fever, vomiting, abdominal pain, etc. (Lopez and Merkoci 2011, Sonawane et al. 2014). A biosensor was devised using polystyrene on which monoclonal antibodies were immobilized which is specific for *Salmonella* which is further attached to conjugate of polyclonal antibody and gold nanoparticles (Dungchai et al. 2008). In another study for the detection of *Salmonella* in milk, optical nanocrystal probe and magnetic nanoparticles were used to devised biosensor. In this biosensor, antibodies attached to magnetic nanoparticles were used to capture bacteria, and later bacteria were separated from magnetic nanoparticles using magnetic field. Further, bacteria were attached to titanium oxide nanoparticles immobilized with antibody specific for *Salmonella* for UV light absorption. Then complex of magnetic nanoparticle—*Salmonella*—titanium oxide was separated from solution by using a magnetic field, and nanocrystals of unbound titanium oxide were analysed (Joo et al. 2012).

10.6 Nanotechnology in Healthy Food Production

Nanotechnology deals with the nanostructures (size varies between 1 and 100 nm) also known as nanomaterials (Pathakoti et al. 2017). These nanomaterials possess some characteristic features which make them more unique, important and useful than there native forms (Gokularaman et al. 2017). Due to their specific physicochemical properties, the nanomaterials are used in various fields such as food preservation, food safety, etc. (Giner et al. 2020). In food nanotechnology, there are mainly two types of nanostructures that are present, i.e. natural and synthetic. The natural nanostructures are mostly food proteins such as milk proteins like casein, polysaccharides, lipids, etc. (Pathakoti et al. 2017), whereas the synthetic nanostructures are polymeric NPs, nanoemulsions and liposomes (Chang and Chen 2005). Nanotechnology in the food industry plays its role in several forms like food packaging material, farming practices, food processing as well as in food itself (Bajpai et al. 2018). Nanotechnology helps maintain sustainability in the food industry as it offers nanosensors for monitoring the physical, chemical and biological properties of the food production process (Alfadul and Elneshwy 2010). It also provides various sensor technologies for contamination (microbial as well as chemical) detection in food (Lin 2012); besides this these technologies are also helpful for controlling pathogen's growth and ensure food safety and also minimize food wastage (Rodrigues et al. 2012). The use of nanotechnology in the food industry is still in its early stage (Singh et al. 2017), and many nanotechnology-based food applications are still under development (Singh et al. 2017). Nanotechnology also provides an opportunity to improve nutrient content in food, make food nutrients and vitamins easily absorbable to the body as well as help in the masking of the unfavourable taste of some extremely healthy foods (Ravichandran 2010).

10.7 Nanotechnology in Food Characteristic Preservation

Rise in industrialization and fast transportation facilities of the intercontinental food become very much common (Sadiku et al. 2019), but this also raises a new challenge in front of food technologists to maintain or preserve the food characteristics for a long time (Moschopoulou et al. 2019). In other words, we can say that shelf life of the packed food must be increased so that every customer at any corner of the globe got the same native taste of the food (Dobruka and Cierpiszewsk 2014). Besides this nanotechnology also contributes to the manufacturing of healthier and safe foods (Gokularaman et al. 2017). Some food ingredients are present in food materials that work on nanoscale commonly known as nanostructures. These nanostructures have specific properties and are playing a very active role in the improvement of food taste, texture and consistency (Gokularaman et al. 2017). They also enhance the shelf life of food (Pradhan et al. 2015). Studies showed that the major cause of food characteristic deterioration in the chemical reactions took place between the various components of food and its surrounding environment (Bajpai et al. 2018; Dimitrijevic et al. 2015). There are several nanomaterials which control or pause these chemical reactions used in the food industry for sustainable food characteristic preservation (Ghosh et al. 2019). Nanotechnology works on a two-way approach to maintain or preserve food characteristics, i.e. modifying the packaging technology and changing the bioactivity of active food components in the packaging environment (Shafiq et al. 2020).

In the food industry, nanotechnology plays a crucial role in the improvements in food taste and its value. Nanoencapsulation is the globally known as the most common and effective method used for the progressive taste along with maintaining a culinary balance (Nakagawa 2014). This technology is applied to those food materials which are extremely reactive such as plant pigments or photoreactive (Shafiq et al. 2020). For example, polymeric nanoparticles can be used for the encapsulation of bioactive compounds such as vitamins and flavonoids which are actively released in the acidic environment of the stomach without any change in their characteristic (Singh et al. 2017). Another nanotechnique is known as nano-emulsion which is created by using fragile bioactive compounds that are soluble in lipids. This technique is used for the improvement of bioavailability and water dispersion (Kumar 2015; Shafiq et al. 2020; Singh et al. 2017). The above-discussed techniques are used for the safe and secure delivery of vitamins, fragile micronutrients and medicines (Haider and Kang 2015).

10.8 Safety Issues and Future Perspective

There is no doubt that over the last few decades the importance and use of nanotechnology in the food sector are rising up; however some objectionable safety concerns associated with nanomaterial are raising the alarm which cannot be neglected. Few studies showed that nanoparticles may adulterate food materials by migrating into it from packaging materials leading to serious health issues. Researchers claim that physicochemical properties of a substance are entirely different in its nanoform with respect to macrostate. As a result any nanomaterial being used in the food sector must possess the GRAS (generally regarded as safe) status as per authority rules and regulation. Though the small quantity of used materials appears to be safe mostly, bioaccumulation within organs and tissues may pose a distant threat. For example, sometimes silica nanoparticles are used as anti-caking agents, but they can be toxic to human lung cells too depending upon the exposure time and pattern. Need for more useful material preparation in present competitive market, pushing the existing knowledge of nanotechnology to go more smaller and sensitive. Food packaging and food safety are two pillar areas for nanouse. However a variety of factors like particle surface morphology, concentration, surface energy, aggregation, etc. may affect dissolution. Significant benefits are now being provided by nanomaterials for food preservation also like protection from moisture, lipids, gases, off-flavours and odours. They are also showing great results in the field of targeted bioactive compound delivery. However, aforementioned heath safety issues still persist, and those challenges must need to be addressed in order to elevate the use of nanomaterial in food the industry. Consumer concerns must to be kept in mind while designing smart useful nanomaterials, and therefore mandatory testing of nanofoods should be a prerequisite before they are introduced to the global market. To be successful in the long run, systematic and focused education of the public is also needed additionally to utilize the maximum benefits of nanofoods.

Acknowledgement The authors express their thanks to Lovely Professional University, Punjab, India, for their necessary support.

References

Adegbeye MJ, Elghandour MMMY, Barbabosa-Pliego A, Monroy JC, Mellado M, Ravi Kanth Reddy P et al (2019) Nanoparticles in equine nutrition: mechanism of action and application as feed additives. J Equine Vet Sci 78:29–37

Alfadul SM, Elneshwy AA (2010) Use of nanotechnology in food processing, packaging and safety review. Afr J Food Agric Nut Dev 10:21 pages

Ali ME, Hashim U, Mustafa S, Man YB, Yusop MH, Bari MF et al (2011) Nanoparticle sensor for label free detection of swine DNA in mixed biological samples. Nanotechnology 22:195503

An J, Zhang M, Wang S, Tang J (2008) Physical, chemical and microbiological changes in stored green asparagus spears as affected by coating of silver nanoparticles-PVP. LWT Food Sci Technol 41:1100–1107

Azeredo HMC, Henrique CLM, Wood D, Williams TG, Roberto JAB, Tara HM (2009) Nanocomposite edible films from mango puree reinforced with cellulose nanofibers. J Food Sci 74:31–35

Aziz N, Fatma T, Varma A, Prasad R (2014) Biogenic synthesis of silver nanoparticles using Scenedesmus abundans and evaluation of their antibacterial activity. J Nanoparticles, Article ID 689419. https://doi.org/10.1155/2014/689419

Aziz N, Faraz M, Pandey R, Sakir M, Fatma T, Varma A, Barman I, Prasad R (2015) Facile algae-derived route to biogenic silver nanoparticles: synthesis, antibacterial and photocatalytic properties. Langmuir 31:11605–11612. https://doi.org/10.1021/acs.langmuir.5b03081

Aziz N, Pandey R, Barman I, Prasad R (2016) Leveraging the attributes of Mucor hiemalis-derived silver nanoparticles for a synergistic broad-spectrum antimicrobial platform. Front Microbiol 7:1984. https://doi.org/10.3389/fmicb.2016.01984

Azizi-Lalabadi M, Ehsani A, Divband B, Alizadeh-Sani M (2019) Antimicrobial activity of Titanium dioxide and Zinc oxide nanoparticles supported in 4A zeolite and evaluation the morphological characteristic. Sci Rep 9:17439

Bajpai VK, Kamle M, Shukla S, Mahato DK, Chandra P, Hwang SK et al (2018) Prospects of using nanotechnology for food preservation, safety, and security. J Food Drug Anal 26:1201–1214

Bayda S, Adeel M, Tuccinardi T, Cordani M, Rizzolio F (2020 Jan) The history of nanoscience and nanotechnology: from chemical–physical applications to nanomedicine. Molecules 25(1):112

Bhushan B (2016) Introduction to nanotechnology: history, status, and importance of nanoscience and nanotechnology education. In: Global perspectives of nanoscience and engineering education. Springer, Cham, pp 1–31

Bhuyan T, Mishra K, Khanuja M, Prasad R, Varma A (2015) Biosynthesis of zinc oxide nanoparticles from *Azadirachta indica* for antibacterial and photocatalytic applications. Mater Sci Semicond Process 32:55–61

Bieberstein A, Roosen J, Marette S, Blanchemanche S, Vandermoere F (2013) Consumer choices for nano-food and nanopackaging in France and Germany. Eur Rev Agric Econ 40:73–94

Bikiaris DN, Triantafyllidis KS (2013) HDPE/Cu-nanofiber nanocomposites with enhanced antibacterial and oxygen barrier properties appropriate for food packaging applications. Mater Lett 93:1–4

de Boer E, Beumer RR (1999) Methodology for detection and typing of foodborne microorganisms. Int J Food Microbiol 50:119–130

Brody AL, Bugusu B, Han JH, Sand CK, Mchugh TH (2008) Innovative food packaging solutions. J Food Sci 73:107–116

Brown EM, Paunesku T, Wu A, Thurn KT, Haley B, Clark J, Priester T et al (2008) Methods for assessing DNA hybridization of peptide nucleic acid–titanium dioxide nanoconjugates. Anal Biochem 383:226–235

Bulbul G, Hayat A, Andreescu S (2016) ssDNA-functionalized nanoceria: a redox-active apta switch for biomolecular recognition. Adv Healthcare Mat 5:822–828

Cavaliere E, De Cesari S, Landini G, Riccobono E, Pallecchi L et al (2015) Highly bactericidal Ag nanoparticle films obtained by cluster beam deposition. nanomedicine: nanotechnology. Biol Med 11:1417–1423

Cerrada ML, Serrano C, Sanchez-Chaves M, Fernandez-Garcia M, Fernandez-Martin F, de Andres A (2008) Self-sterilized EVOH TiO_2 nanocomposites: effect of TiO_2 content on biocidal properties. Adv Funct Mater 18:1949–1960

Chang YC, Chen DGH (2005) Adsorption kinetics and thermodynamics of acid dyes on a carboxymethylated chitosan-conjugated magnetic nano-adsorbent. Macromol Biosci 5:254–261

Chatterjee AK, Chakraborty R, Basu T (2014) Mechanism of antibacterial activity of copper nanoparticles. Nanotechnology 25:135101

Cheli F, Pinoti L, Campagnoli A, Fusi E, Rebuci R, Baldi A (2008) Mycotoxin analysis, mycotoxin-producing fungi assays and mycotoxin toxicity bioassays in food mycotoxin monitoring and surveillance. Ital J Food Sci 20:447–462

Chien YY, Jan MD, Adak AK, Tzeng HC, Lin YP, Chen YJ et al (2008) Globotriose functionalized gold nanoparticles as multivalent probes for Shiga-like toxin. Chembiochem 9:1100–1109

Cioffi N, Torsi L, Ditaranto N, Tantillo G, Ghibelli L, Sabbatini L et al (2005) Copper nanoparticle/polymer composites with antifungal and bacteriostatic properties. Chem Mater 17:5255–5262

Couch LM, Wien M, Brown JL, Davidson P (2016) Food nanotechnology: proposed uses, safety concerns and regulations. Agro Food Ind Hitech 27:36–39

Dankovich TA, Gray DG (2011) Bactericidal paper impregnated with silver nanoparticles for point-of-use water treatment. Environ Sci Technol 45:1992–1998

Dekkers S, Krystek P, Peters RJ, Lankveld DX, Bokkers BG, van Hoeven-Arentzen PH et al (2011) Presence and risks of nanosilica in food products. Nanotoxicology 5:393–405

Dimitrijevic M, Karabasil N, Boskovic M, Teodorovic V, Vasilev D, Djordjevic V et al (2015) Safety aspects of nanotechnology applications in food packaging. Procedia Food Sci 5:57–60

Dingman JS (2008) Nanotechnology: its impact on food safety, guest commentary. J Environ Health 70(6):47–50

Dobruka R, Cierpiszewsk R (2014) Active and intelligent packaging food—research and development—a review. Poland J Food Nutra Sci 64:7–15

Duncan TV (2011) Applications of nanotechnology in food packaging and food safety: barrier materials, antimicrobials and sensors. J Colloid Interface Sci 363:1–24

Dungchai W, Siangproh W, Chaicumpa W, Tongtawe P, Chailapakul O (2008) *Salmonella typhi* determination using voltammetric amplification of nanoparticles: a highly sensitive strategy for metalloimmunoassay based on a copper-enhanced gold label. Talanta 77:727–732

Elkloub K, El Moustafa ME, Ghazalah AA, Rehan A (2015) Effect of dietary nanosilver on broiler performance. Int J Poult Sci 14:177–182

Ezhilarasi PN, Karthik P, Chhanwal N, Anandharamakrishnan C (2013) Nanoencapsulation techniques for food bioactive components: a review. Food Bioprocess Technol 6:628–647

Farhoodi M (2016) Nanocomposite materials for food packaging applications: characterization and safety evaluation. Food Eng Rev 8:35–51

Feng T, Xiao Z, Tian H (2010) Recent patents on nano flavour preparation and its application. Recent Pat Food Nutr Agric 2:243–250

Fondevila M, Herrer R, Casallas MC, Abecia L, Ducha JJ (2009) Silver nanoparticles as a potential antimicrobial additive for weaned pigs. Anim Feed Sci Tech 150:259–269

Garcia-Ruiz A, Crespo J, Lopez-de-Luzuriaga JM, Olmos ME, Monge M, Rodriguez-Alfaro MP et al (2015) Novel biocompatible silver nanoparticles for controlling the growth of lactic acid bacteria and acetic acid bacteria in wines. Food Cont 50:613–619

Garde-Cerdan T, Lopez R, Garijo P, Gonzalez-Arenzana L, Gutierrez AR, Lopez-Alfaro I et al (2014) Application of colloidal silver versus sulfur dioxide during vinification and storage of Tempranillo red wines. Aust J Grape Wine Res 20:51–61

Ghosh C, Bera D, Roy L (2019) Role of nanomaterials in food preservation. In: Microbial nanobionics. Springer, Cham, pp 181–211

Giner ST, Prieto C, Lagaron JM (2020) Nanomaterials to enhance food quality, safety, and health impact. Nano 10:941

Gokularaman S, Cruz SA, Pragalyaashree M, Nishadh A (2017) Nanotechnology approach in food packaging-review. J Pharm Sci Res 9:1743–1749

Gupta A, Eral HB, Hatton TA, Doyle PS (2016) Nanoemulsions: formation, properties and applications. Soft Matter 12:2826–2841

Haider A, Kang IK (2015) Preparation of silver nanoparticles and their industrial and biomedical applications: a comprehensive review. Adv Mat Sci Eng 2015:1–16

Hayat A, Paniel N, Rhouati A, Marty JL, Barthelmebs L (2012) Recent advances in ochratoxin A-producing fungi detection based on PCR methods and ochratoxin A analysis in food matrices. Food Cont 26:401–415

Izquierdo-Canas PM, Garcia-Romero E, Huertas-Nebreda B, Gomez-Alonso S (2012) Colloidal silver complex as an alternative to sulphur dioxide in winemaking. Food Cont 23:73–81

Jain KK (2005) Nanotechnology in clinical laboratory diagnostics. Clin Chim Acta 358:37–54

Jin T, Sun D, Su JY, Zhang H, Sue H-J (2009) Antimicrobial efficacy of zinc oxide quantum dots against enteritidis, and O157:H7. J Food Sci 74(1):M46–M52

Joo J, Yim C, Kwon D, Lee J, Shin HH, Cha HJ et al (2012) A facile and sensitive detection of pathogenic bacteria using magnetic nanoparticles and optical nanocrystal probes. Analyst 137:3609–3612

Joshi N, Jain N, Pathak A, Singh J, Prasad R, Upadhyaya CP (2018) Biosynthesis of silver nanoparticles using *Carissa carandas* berries and its potential antibacterial activities. J Sol-Gel Sci Techn 86(3):682–689

Kaittanis C, Santra S, Perez JM (2010) Emerging nanotechnology based strategies for the identification of microbial pathogenesis. Adv Drug Deliv Rev 62:408–423

Kim I, Viswanathan K, Kasi G, Thanakkasaranee S, Sadeghi K, Seo J (2020) ZnO Nanostructures in active antibacterial food packaging: preparation methods, antimicrobial mechanisms, safety issues, future prospects, and challenges. Food Rev Int. https://doi.org/10.1080/87559129.2020.1737709

Kubacka A, Diez MS, Rojo D, Bargiela R, Ciordia S, Zapico I et al (2014) Understanding the antimicrobial mechanism of TiO_2-based nanocomposite films in a pathogenic bacterium. Sci Rep 4:4134

Kumar LY (2015) Role and adverse effects of nanomaterials in food technology. J Toxicol Health 2:1–11

Langer R, Peppas NA (2003) Advances in biomaterials, drug delivery, and bionanotechnology. AICHE J 49:2990–3006

Li Q, Mahendra S, Lyon DY, Brunet L, Liga MV, Li D et al (2008) Antimicrobial nanomaterials for water disinfection and microbial control: potential applications and implications. Water Res 42:4591–4602

Lin M (2012) Nanotechnology-based approaches for rapid detection of chemical and biological contaminants in foods. Nanotechnol Food Bev Nutra Ind 2012:317–334

Lin YH, Chen SH, Chuang YC, Lu YC, Shen TY, Chang CA et al (2008) Disposable amperometric immunosensing strips fabricated by Au nanoparticles-modified screen-printed carbon electrodes for the detection of foodborne pathogen *Escherichia coli* O157:H7. Biosens Bioelectron 23:1832–1837

Lopez BP, Merkoci A (2011) Nanomaterials based biosensors for food analysis applications. Trends Food Sci Technol 2:625–639

Majid I, Nayik GA, Dar MS, Nanda V (2018) Novel food packaging technologies: innovations and future prospective. J Saudi Soc Agric Sci 17:454–462

Manguiat LS, Fang TJ (2013) Evaluation of DADTM kits for the detection of food-borne pathogens in chicken- and meat based street-vended foods. J Food Drug Anal 21:198–205

Manso S, Cacho-Nerin F, Becerril R, Nerin C (2013) Combined analytical and microbiological tools to study the effect on *Aspergillus flavus* of cinnamon essential oil contained in food packaging. Food Cont 30:370–378

Mao X, Yang L, Su X, Yi Y (2006) A nanoparticle amplification based quartz crystal microbalance DNA sensor for detection of *Escherichia coli* O157:H7. Biosens Bioelectron 21:1178–1185
Medina-Jaramillo C, Ochoa-Yepes O, Bernal C, Fama L (2017) Active and smart biodegradable packaging based on starch and natural extracts. Carbohydr Polym 176:187–194
Mihindukulasuriya SDF, Lim LT (2014) Nanotechnology development in food packaging: a review. Trends Food Sci Technol 40:149–167
Moreno MA, Orqueda ME, Gomez-Mascaraque LG, Isla MI, Lopez-Rubio A (2019) Crosslinked electrospun zein-based food packaging coatings containing bioactive chilto fruit extracts. Food Hydrocoll 95:496–505
Moschopoulou E, Moatsou G, Syrokou MK, Paramithiotis S, Drosinos EH (2019) Food quality changes during shelf life. Food Qual Shelf Life 2019:1–31
Nakagawa K (2014) Nano-and microencapsulation of flavor in food systems. In: Nano-and microencapsulation for foods. John Wiley & Sons, Inc., Hoboken, NJ, pp 249–272
Naoto S, Hiroshi O, Mitsutoshi N (2009) Micro and nanotechnology for food processing. (Food safety series) resource: engineering and technology for a sustainable. World Am Soc Agri Eng 16:19
Nath S, Kaittanis C, Tinkham A, Perez JM (2008) Dextran-coated gold nanoparticles for the assessment of antimicrobial susceptibility. Anal Chem 80:1033–1038
Nile SH, Baskar V, Selvaraj D, Nile A, Xia J, Kai G (2020) Nanotechnologies in food science: applications, recent trends, and future perspectives. Nano-Micro Lett 12:45
Orsuwan A, Shankar S, Wang LF, Sothornvit R, Rhim JW (2016) Preparation of antimicrobial agar/banana powder blend films reinforced with silver nanoparticles. Food Hydrocoll 60:476–485
Pathakoti K, Manubolu M, Hwanga HM (2017) Nanostructures: current uses and future applications in food science. J Food Drug Anal 25:245–253
Petchwattana N, Covavisaruch S, Wibooranawong S, Naknaen P (2016) Antimicrobial food packaging prepared from Poly (Butylene Succinate) and Zinc Oxide. Measurement 93:442–448
Petzinger E, Ziegler K (2000) Ochratoxin A from a toxicological perspective. J Vet Pharmacol Ther 23:91–98
Pineda L, Chwalibog A, Sawosz E, Lauridsen C, Engberg R, Elnif J et al (2012) Effect of silver nanoparticles on growth performance, metabolism and microbial profile of broiler chickens. Arch Anim Nutr 66:416–429
Pinto RJB, Daina S, Sadocco P, Neto CP, Trindade T (2013) Antibacterial activity of nanocomposites of copper and cellulose. Biomed Res Int 2013:280512
Powers KW, Brown SC, Krishna VB, Wasdo SC, Moudgil BM, Roberts SM (2006) Research strategies for safety evaluation of nanomaterials. Part VI. Characterization of nanoscale particles for toxicological evaluation. Toxicol Sci 90:296–303
Prasad R, Kumar V, Prasad KS (2014) Nanotechnology in sustainable agriculture: present concerns and future aspects. Afr J Biotechnol 13(6):705–713
Pradhan N, Singh S, Ojha N, Srivastava A, Barla A, Rai V et al (2015) Facets of nanotechnology as seen in food processing, packaging, and preservation industry. Bio Med Res Int 2015:365672
Prasad R, Kumar V, Kumar M (2017a) Nanotechnology: food and environmental paradigm. Springer Nature Singapore Pte Ltd., Singapore. ISBN 978-981-10-4678-0
Prasad R, Bhattacharyya A, Nguyen QD (2017b) Nanotechnology in sustainable agriculture: recent developments, challenges, and perspectives. Front Microbiol 8:1014. https://doi.org/10.3389/fmicb.2017.01014
Ranjan S, Dasgupta N, Chakraborty AR, Samuel SM, Ramalingam C, Shanker R et al (2014) Nanoscience and nanotechnologies in food industries: opportunities and research trends. J Nanopart Res 16:2464
Ravichandran R (2010) Nanotechnology applications in food and food processing: innovative green approaches, opportunities and uncertainties for global market. Int J Green Nanotechnol Phys Chem 1:72–96
Renton A (2006) Welcome to the world of nano foods. http://observer.guardian.co.uk/foodmonthly/futureoffood/story/0,1971266,00.html

Rodrigues SM, Demokritou P, Dokoozlian N, Hendren CO, Karn B, Mauter MS et al (2012) Nanotechnology for sustainable food production: promising opportunities and scientific challenges. Environ Sci Nano 4:767–781

Rosi NL, Mirkin CA (2005) Nanostructures in biodiagnostics. Chem Rev 105:1547–1562

Sadiku MNO, Musa SM, Ashaolu TJ (2019) Food industry: an introduction. Int J Trend Sci Res Dev 3:128–130

Salami-Kalajahi M, Haddadi-Asl V, Roghani-Mamaqani H (2012) Study of kinetics and properties of polystyrene/silica nanocomposites prepared via in situ free radical and reversible addition-fragmentation chain transfer polymerizations. Sci Iran 19:2004–2011

Salyers AA, Whitt DD (2002) Bacterial pathogenesis: a molecular approach, 2nd edn. ASM Press, Washington DC

Sari P, Mann B, Kumar R, Singh RRB, Sharma R, Bhardwaj M, Athira S (2015) Preparation and characterization of nanoemulsion encapsulating curcumin. Food Hydrocol 43:540–546

Sawai J (2003) Quantitative evaluation of antibacterial activities of metallic oxide powders (ZnO, MgO and CaO) by conductimetric assay. J Microbiol Methods 54(2):177–182

Saxena A, Maity T, Paliwal A, Wadhwa S (2017) Technological aspects of nanoemulsions and their applications in the food sector. In: Oprea AE, Grumezescu AM (eds) Nanotechnology applications in food: flavor, stability, nutrition, and safety. Academic Press, pp 129–152

Schirmer BC, Heiberg R, Eie T, Moretro T, Maugesten T, Carlehog M (2009) A novel packaging method with a dissolving CO_2 headspace combined with organic acids prolongs the shelf life of fresh salmon. Int J Food Microbiol 133:154–160

Sekhon BS (2010) Food nanotechnology—an overview. Nanotechnol Sci Appl 3:1–15

Shafiq M, Anjum S, Hano C, Anjum I, Abbasi BH (2020) An overview of the applications of nanomaterials and nano-devices in the food industry. Foods 9:1–27

Sharma C, Dhiman R, Rokana N, Panwar H (2017) Nanotechnology: an untapped resource for food packaging. Front Microbiol 8:1735

Sheikh FA, Kanjawal MA, Saran S, Chung WJ, Kim H (2011) Polyurethane nanofibers containing copper nanoparticles as future materials. Appl Surf Sci 257:3020–3026

Singh T, Shukla S, Kumar P, Wahla V, Bajpai VK, Rather IA (2017) Application of nanotechnology in food science: perception and overview. Front Microbiol 8:1501–1507

Singh S, Kumar V, Dhanjal DS, Datta S, Prasad R, Singh J (2020) Biological biosensors for monitoring and diagnosis. In: Singh J, Vyas A, Wang S, Prasad R (eds) Microbial biotechnology: basic research and applications. Springer Nature Singapore, Singapore, pp 317–336

Sirelkhatim A, Mahmud S, Seeni A, Kaus NHM, Ann LC, Bakhori SKM et al (2015) Review on zinc oxide nanoparticles: antibacterial activity and toxicity mechanism. Nano Micro Lett 7:219–242

Sonawane SK, Arya SS, LeBlanc JG, Jha N (2014) Use of nanomaterials in the detection of food contaminants. Eur J Nutr Food Saf 4:301–317

Sorrentino A, Gorrasi G, Vittoria V (2007) Potential perspectives of bio-nanocomposites for food packaging applications. Trends Food Sci Technol 18:84–95

Tang D, Tang J, Su B, Chen G (2011) Gold nanoparticles-decorated amine-terminated poly (amidoamine) dendrimer for sensitive electrochemical immunoassay of brevetoxins in food samples. Biosens Bioelectron 26:2090–2096

Thangadurai D, Sangeetha J, Prasad R (2020) Nanotechnology for food, agriculture, and environment. Springer International Publishing, Cham. ISBN 978-3-030-31937-3. https://www.springer.com/gp/book/9783030319373

Valdes MG, Gonzalez ACV, Calzon JAG, Dıaz-Garcıa ME (2009) Analytical nanotechnology for food analysis. Microchim Acta 166:1–19

Weiss J, Takhistov P, McClements J (2006) Functional materials in food nanotechnology. J Food Sci 71:R107–R116

Wu Z, Huang X, Li YC, Xiao H, Wang X (2018) Novel chitosan films with laponite immobilized Ag nanoparticles for active food packaging. Carbohydr Polym 199:210–218

Yadav SK (2017) Tissue science & engineering realizing the potential of nanotechnology for agriculture and food technology. J Tissue Sci Eng 8:8–11

Yadav L, Tripathi RM, Prasad R, Pudake RN, Mittal J (2017) Antibacterial activity of Cu nanoparticles against *E. coli*, *Staphylococcus aureus* and *Pseudomonas aeruginosa*. Nano Biomed Eng 9(1):9–14. https://doi.org/10.5101/nbe.v9i1.p9-14

Yang M, Kostov Y, Rasooly A (2008) Carbon nanotubes based optical immunodetection of staphylococcal enterotoxin B (SEB) in food. Int J Food Microbiol 127:78–83

Yang M, Kostov Y, Bruck HA, Rasooly A (2009) Gold nanoparticle based enhanced chemiluminescence immunosensor for detection of staphylococcal enterotoxin B (SEB) in food. Int J Food Microbiol 133:265–271

Yang R, Zhou Z, Sun G, Gao Y, Xu J, Strappe P et al (2015) Synthesis of homogeneous protein-stabilized rutin nanodispersions by reversible assembly of soybean (*Glycine max*) seed ferritin. RSC Adv 5:31533–31540

Yu Z, Wang W, Kong F, Lin M, Mustapha A (2019) Cellulose nanofibril/silver nanoparticle composite as an active food packaging system and its toxicity to human colon cells. Int J Biol Macromol 129:887–894

Zhang Y, Zhu W, Lu Y, Gao Z, Gu J (2014) Nano-scale blocking mechanism of MMT and its effects on the properties of polyisocyanate-modified soybean protein adhesive. Ind Crops Prod 57:35–42

Zhong M, Yang L, Yang H, Cheng C, Deng W, Tan Y et al (2019) An electrochemical immunobiosensor for ultrasensitive detection of *Escherichia coli* O157:H7 using CdS quantum dots-encapsulated metal-organic frameworks as signal-amplifying tags. Biosens Bioelectron 126:493–500

Zodrow K, Brunet L, Mahendra S, Li D, Zhang A, Li Q et al (2009) Polysulfone ultrafiltration membranes impregnated with silver nanoparticles show improved biofouling resistance and virus removal. Water Res 43:715–723