Nanotechnology in agro-food: From field to plate

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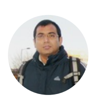

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Review

Nanotechnology in agro-food: From field to plate

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ABSTRACT

Application of nanotechnology in the agro-food sector is one of the fastest growing fields in nano-research. The increase in number of the publications, patents and intellectual property rights in the field of nano-agri-food and recent research trends in food processing, packaging, nutraceutical delivery, quality control and functional food is by itself an evidence of the above statement. Government organizations, scientists, inventors as well as industries are coming up with new techniques, protocols and products that have a direct application of nanotechnology in agriculture and food products.

This review provides a detailed overview of the application of nanotechnology in the field of agriculture, and food science & technology. Additionally, a brief idea about the classification of nanomaterials, synthesis and characterization techniques is discussed. Some exciting thoughts are also discussed on nanotechnological applications in agricultural practices including nano-agri for enhanced productivity, agricultural water quality management (WQM), product processing, storage and quality control with nano-sensors. The risk assessment and safety concerns with respect to nano agro-food research have also been highlighted.

Contents

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1. Introduction

Nanotechnology, the vast field of the 21st century, is making a very significant impact on the world's economy, industry and people's lives (Gruere, Narrod, & Abbott, 2011; Scott & Chen, 2003; Kingsley, Ranjan, Dasgupta & Saha, 2013). Nanotechnology in agriculture is focusing on the various applications of nano-food-science in relation to safety, packaging, among others. Nanostructured materials have a significant influence on the manufacturing, packaging and storage of food thus exhibiting unique physicochemical properties that open windows of opportunity for the creation of new, high performance materials. Recent application of nanotechnology in food production includes development of nano-sized food ingredients and additives, delivery systems for bioactive compounds and innovative food packaging (Ranjan et al., 2014). Different types of nanomaterials (NMs) used in agro food industry are nanoparticles (NPs), nanoclays (NCs) and nanoemulsions (NEs). These can be synthesized by a number of methods and have many applications in the agri-food sector (Table 1).

The physicochemical property of NPs greatly depends upon its surface characteristics. Unlike chemical compounds, where the characterization is usually confined to chemical composition and purity determination, nanomaterials demand comprehensive characterization. The exact properties of nanoparticles and their correlation with its biological activity are poorly understood. Therefore, an extensive and complete characterization, including size distribution, shape, surface area, surface chemistry, crystallinity, porosity, agglomeration state, surface charge, solubility, *etc.* is recommended for nanomaterials. It is to be highlighted that in most cases, the availability of facilities determines the type of characterization performed rather than the study design or experimental needs (Dhawan & Sharma, 2010). Size is the most important parameter that should be considered for characterization, and it is critical for determining the interactions of nanoparticles with living systems (Berhanu et al., 2009; Sayes & Warheit, 2009; Warheit, 2008; Powers, Palazuelos, Moudgil, & Roberts, 2007). The size of the nanoparticles can be regulated by the methods used for their synthesis. There is no uniform process for the synthesis of nanoparticles at the laboratory and industrial scales. The process varies considerably in different research institutions and industrial scale laboratories. Sol–gel technique, spray-drying process, and microemulsion processing are few of the commonly used method stages (Kumar & Dhawan, 2013a). Sol–gel technique is one of the most commonly used techniques for the synthesis of ENMs, due to its simplicity and flexibility in controlling the properties of the final products at various stages (Kumar & Dhawan, 2013a, 2013b). A number of methods and technologies are available for determining the size and other physico-chemical properties of nanoparticles: dynamic light scattering (DLS), Brunauer–Emmett–Teller (BET), atomic force microscopy (AFM), scanning electron microscopy (SEM), transmission electron microscopy (TEM), UV–vis spectrophotometer and X-ray diffractometer (XRD), *etc.* are some of the techniques commonly employed for the characterization of nanoparticles (Kumar, Pandey, Singh, Shanker, & Dhawan, 2011a, 2011b, 2011c).

2. Nanotechnological applications in agricultural practices

Changing climate, urbanization, and sustainable use of natural resources and environmental issues like runoff and accumulation of pesticides and fertilizers are some of the major challenges faced by agriculturists worldwide. These problems are further intensified by an alarming increase in the demand to feed an estimated population of 6–9 billion by 2050 (Chen & Yada, 2011). This scenario of a rapidly developing and complex agricultural system exists mainly in developing countries and greater challenges will be posed to these countries as agriculture forms the backbone of the national economy of such countries.

2.1. Nano-agri and enhanced productivity

Applications of nanotechnology in materials science and biomass conversion technologies applied in agriculture are the basis of providing food, feed, fiber, fire and fuels. Through advancement in nanotechnology, a number of state-of-the-art techniques are available for the improvement of precision farming practices that will allow precise control at a nanometer scale. Nanotechnology can also be an alternative source of fertilizers. It was observed that SiO_2 nanoparticles enhanced germination in tomato (*Lycopersicum esculentum*) seeds (Manzer & Mohamed, 2014). Nanoscale carriers and fabricated xylem vessels are some of the applications of nanotechnology in the agriculture sector. Detailed overviews of application of nanoscience in agricultural techniques have been provided in Fig. 1.

2.1.1. Nanoscale carriers

Nanoscale carriers can be utilized for the efficient delivery of fertilizers, pesticides, herbicides, plant growth regulators, *etc*. Encapsulation and entrapment, polymers and dendrimers, and surface ionic and weak bond attachments are some of the mechanisms involved in the efficient delivery, better storage and controlled release of products (Pandey, Zahoor, Sharma, & Khuller, 2003; Jordan, Jacob, Tannenbaum, Sharaf, & Jasiuk, 2005; Kumar, Khan, & Dhawan, 2014). Nanoscale carriers can be designed in such a way that they can anchor the plant roots to the surrounding soil structure and organic matter thus reducing chemical runoff and alleviating environmental problems. This can only be possible through the molecular and conformational mechanisms between the targeted nanoscale structures and matter in soil (Johnston, 2010). These advancements will help in increasing the bioavailability of active ingredients to the plant, thereby reducing the amount of effort and waste product. Cai et al. (2014) developed nanoclay which can be added to traditional fertilizer to retain nitrogen and prevent its leaching, thus providing sufficient nutrition to crops. Many nanoemulsions have been formulated with the application as herbicide and pesticide — as discussed in Table 1 (Chaw et al., 2012, 2013; Megha et al., 2014).

2.1.2. Fabricated xylem vessels

Recent advancements in nanofabrication and characterization tools resulted in studying the physico-chemical and biological interactions between plant cell bodies and various disease-causing organisms. These tools are useful in understanding the mechanisms involved and can help to improve the strategies for the treatment of such diseases (Cursino et al., 2009). For example, in the past, to study xylem-inhabiting bacteria, changes in bacterial populations were monitored through destructive sampling techniques at different distances from inoculation sites. But traditional methods like this do not provide information about colonization, film development, and subsequent movement and re-colonization of bacterial population at new areas. It was only through the discovery of micro-fabricated xylem vessels with nano-sized features that the study of the above mechanisms was possible (Zaini, Leonardo, Hoch, & Burr, 2009). Lars, 2012 have reported about a probe, which can be inserted into the xylem vessel at the root base which can monitor xylem pressure, the radial electrical gradients in the root and activity of particular ions (Lars, 2012). A detailed description of nanotechnology in fabricated xylem vessels has been described by Bandyopadhyay, Jose, & Jorge (2013) and fabricated xylem system in the form of nanoliter/picoliter scale fluidic systems has been summarized (Morgan, Omar, & Jong, 2013). Biomimicking micro/nanofabricated xylem vessels system by using microbes, researchers have looked at the attachment behavior of *Xylella fastidiosa* (Leonardo et al., 2007) and *Escherichia coli* (Bunpot, Michael, & Glenn, 2011) in microfluidic flow chambers mimicking plant xylem. Biomimicking of capillary action has been developed by using micro/nanofabrication — which may have future application in fabricated xylem vessel development (Qian, Jiaju, & Yuying, 2014; Bharat, 2011). To control the photoluminescent emission Carlos, Dachamir, Carlo, & Cordt (2013) have used ZnO and Al_2O_3 nanoparticles in *Calamus rotang* plant in natural xylem samples.

2.2. Agricultural water quality management (WQM)

At present, provision of clean and abundant fresh water for human use and industrial applications such as agriculture is one of the most important challenges faced by the world (Vörösmarty et al., 2010). According to a survey (Cross et al., 2009), more than one billion people in the world is deprived of clean water and the situation is getting worse. In the near future, it has been estimated that the average water supply per person will drop by a factor of one third, which will result in the avoidable premature death of millions of people (Cross et al., 2009). A large amount of fresh water is required in agriculture, but in turn, it contributes to groundwater pollution through the use of pesticides, fertilizers and other agricultural chemicals. To combat this problem and to treat the large amount of waste water produced, novel sustainable and cost effective technologies will be required. During the treatment of wastewater, critical issues like water quality and quantity, treatment and reuse, safety due to chemical and biological hazards, monitoring and censoring, *etc.* should be considered. Research and development in nanotechnology have enabled us to find novel and economically feasible solutions for remediation and purification of wastewater. Accessible water resources are mostly contaminated with water-borne pathogenic microorganisms (like cryptosporidium, coliform bacteria, virus, *etc.*), various salts and metals (Cu, Pb, As, *etc.*), runoff agricultural chemicals, thousands of compounds considered as pharmaceuticals and personal care products (PPCP), endocrine disrupting compounds (EDCs) and radioactive contaminants. These water resources are contaminated by oil and gas production, mining activities, natural leaching and anthropogenic activities (Speed, Barnard, Arber, Budd, & Johns, 1987; Jasra, Mody, & Bajaj, 1999). Nano-scale zero-valent iron can be used for the treatment of distillery wastewater (Homhoul, Pengpanich, & Hunsom, 2011). For improving water quality, nanotechnology has provided novel solutions (Fig. 2).

2.2.1. Nano-oligodynamic metallic particles

Physico-chemical microbial disinfection systems like chlorine dioxide, ozone and ultraviolet are being commonly used in developed countries, but most of the developing countries do not have these systems due to the lack of large infrastructure. The need of the hour is to search and develop alternate cost-effective technologies. Nanotechnology based oligodynamic metallic particles have the ability to make water free from microbes. Among these nanomaterials, silver is the most promising one as it is both bactericidal and viricidal due to the production of reactive oxygen species (ROS) that cleaves DNA and can be utilized for a wide range of applications. Other properties include ease of use, its charge capacity, high surface-to-volume ratios, crystallographic structure and adaptability to various substrates (Nangmenyi & Economy, 2009; Faunce, Alex, & Angus, 2014; Chen & Yada, 2011).

2.2.2. Photocatalysis

Visible light photocatalysis of transition metal oxides is another nanoscale technological development that produces NPs, nanoporous fibers and nanoporous foams that can be used for microbial disinfection (Li, Wu, & Shang, 2009) and for the removal of organic contaminants like PPCPs and EDCs. Moreover, tubular nanostructures, embedded into microbial cell wall, can disrupt cell structure resulting in the leakage of intracellular compounds, and ultimately cell death. It involves the reaction of catalyst (NPs) with chemical compounds in the presence of light. Here, when NPs of specific compounds are subjected to UV light, the electrons in the outermost shell (valence electrons) are excited resulting in the formation of electron hole pairs, *i.e.*, negative electrons and positive holes (Zhaoxia et al., 2011). These are excellent oxidizing agents and include metal oxides like TiO_2 (Khataee, Fathinia, & Joo, 2013), silver (Zhaoxia et al., 2011), gold (Vongani, Yasin, & Tebello, 2011), ZnO (Li & Haneda, 2003; Mohammad, Sunandan, & Joydeep, 2011), SnO_2 (Ko, Kang, Park, Lee, & Kim, 2009), platinum (Zhi & Wenfeng, 2014), Ag-α–Fe_2O_3 nanocomposites (Shaofeng et al., 2014),

Table 1
A brief perspective of application of nanotechnology in food science and its allied fields.

S. no.	Particle	Preparation/synthesis methods	Main applications	References
1	Nanoparticle			
1.a.	Organic nanoparticle (nanoscale vesicular system)	Nanoprecipitation, emulsion–diffusion, double emulsification, emulsion–coacervation, polymer-coating, layer by-layer	Enhanced nutritional value of food, drug delivery/controlled release of drug, food enhancement, encapsulation of active components	Quintanar, Allémann, Fessi, and Doelker (1998), Letchford and Burt (2007), Anton, Benoit, and Saulnier (2008), Fessi, Puisieux, Devissaguet, Ammoury, and Benita (1989), Devissaguet, Fessi, and Puisieux (1991), Radtchenko, Sukhorukov, and Möhwald (2002) and Ezhilarasi, Karthik, Chhanwal, and Anandharamakrishnan (2012)
			Recently a new class of water-soluble red fluorescent ONP have been prepared with an application of cell imaging which further can be used in the development of nano-sensors.	Xiqi, Xiaoyong, Bin, Yaling, and Yen (2014)
			With the future perspective of dye removal (remediation) from soil as well as water — fluorescent organic nanoparticles that combine the dye have been developed. These facilely incorporated polymeric nanoparticles showed high water dispersibility, uniform size, strong red fluorescence and excellent biocompatibility making them promising in water purification, nano-sensor development for water as well as agricultural products.	Zhang et al. (2014)
1.b.	Inorganic nanoparticles (INP) (inorganic ingredients manufactured at the nanoscale)	Gas phase INP synthesis method (flamed spray synthesis, synthesis by laser induced gas evaporation and plasma based synthesis) and liquid phase INP synthesis method (co-precipitation method and sol–gel approach)	Antimicrobial agent, storage and packaging unit, catalyst, tooth repair, and sensors production of metal NPs	Food Safety Authority of Ireland (2008), Layman (1995), Osullivan (1991), Pratsinis (1998), Stark, Pratsinis, and Baiker (2002), Ulrich (1984), Schulz, Stark, Maciejewski, Pratsinis, and Baiker (2003), Stark, Grunwaldt, Maciejewski, Pratsinis, and Baiker (2005), Stark, Maciejewski, Madler, Pratsinis, and Baiker (2003), Stark, Wegner, Pratsinis, and Baiker (2001), Stark, Pratsinis, and Baiker (2002), Athanassiosu, Grass, and Stark (2006), Athanassiou, Mensing, and Stark (2007) and Athanassiou, Grass, Osterwalder, and Stark (2007)
			Cellulose-based bactericidal nanocomposites containing silver nanoparticles have been developed — bactericidal properties and improved nanocomposite properties were found. Further it has been concluded that these properties may have future applications in active packaging of food and agricultural products.	Márcia, Luiz, and Valtencir (2012)
			Also, silver NPs incorporated into carboxymethylcellulose films have been studied for their antimicrobial properties for food and agricultural products and found suitable for the same.	Siqueira et al. (2014)
			They are having a role in nanoreinforcement packaging, smart packaging, *etc.*	Ranjan et al. (2014)

2	Nano-clays (NCs): (fine-grained minerals having sheet-like geometry)	They are synthesized mainly by top-down approach from suitable materials.	Geology, agriculture, construction, engineering, process industries, and environmental applications, in drug products as excipients and active agents, improve the mechanical strength of biopolymers	Garrido-Ramirez, Theng, and Mora (2010), Carretero and Pozo (2009) and Carretero and Pozo (2010)
			Recently NCs have been found to have application in sensor development	Grasielli et al. (2012)
			Nanoremediation — mainly dye, pesticides, *etc.*	Gholam, Javad, Zeinab, Shiva, and Hossein (2013) and Yan, Andrew, Stephen, and Mikel (2014)
			Used in the manufacture of biodegradable nanocomposite materials	Jin and Zhong (2013)
			Used in nanoreinforcement packaging, nanocomposite active and nanocomposite smart packaging	Aníbal, María, Margarita, María, and Nelio (2014) and Ranjan et al. (2014)
3	Nanoemulsions (lipid phase dispersed in an aqueous continuous phase)	High-energy (high-pressure homogenization, ultrasound, high-speed devices) and low energy approaches (membrane emulsification, spontaneous emulsification, solvent displacement, emulsion inversion point, phase inversion point)	Encapsulate functional food components	Ranjan et al. (2014), Acosta (2009), McClements, Decker, and Weiss (2007), Tadros, Izquierdo, Esquena, and Solans (2004) and Finke et al. (2014)
			Increase bioavailability and bioactivity	Hira et al. (2014), Ranjan et al. (2014), Joseph and Heike (2014), Keun et al. (2012) and Ghosh, Amitava, and Natarajan (2014)
			Antimicrobial, antihelminthic, insecticidal, pesticidal, weedicidal	Karthikeyan, Bennett, Ralph, and Valerie (2012), Karthikeyan, Bennett, Ralph, and Valerie (2011), Megha, Saurabh, Patanjali, Naik, and Satyawati (2014), Chaw et al. (2013), Chaw et al. (2012) and Francesco, Marianna, Mariarosaria, and Giovanna (2012)
			Nanoremediation	Alexey and Simon (2014), Shams and Ahi (2013)

lanthanum ferrite nanoparticles (Abazari, Soheila, & Lotf, 2014), *etc.*, as well as sulfides like ZnS (Feigl, Russo, & Barnard, 2010) and CdS (Xingyuan et al., 2014). As the size of particles decreased, the atoms present on the boundary increased, which results in a tremendous increase in chemical reactivity and other physico-chemical properties related to some specific conditions such as photocatalysis, photoluminescence, *etc.* So this process can be used for the decomposition of many toxic compounds such as pesticides, which take a long time to degrade under normal conditions (Malato et al., 2002). Ankita and Vidya (2014) have remediated Reactive Blue 220 dye with sunlight induced photocatalytic degradation by using Ag core–TiO_2 shell (Ag@TiO_2) nanoparticles. They found a higher rate of photocatalysis under sunlight as compared to UV light and also Ag@TiO_2 is a better photocatalyst than Degussa-P25, TiO_2 NP and Ag doped TiO_2 NP. It can be noted that Degussa-P25 is an existing product with these properties manufactured by Evonik Degussa India Pvt. Ltd. Their basic research may turn up with a development of WQM instruments and/or other agricultural engineering devices (Ankita & Vidya, 2014). Pigeot-Rémy et al. (2011) have used TiO_2 NP for photocatalysis and disinfection of water and also to decrease target bacterial load and a rectangular photoreactor has been designed and optimized (Fathinia & Khataee, 2013). Recent research trend is shifting towards finding doped nanoparticles with better efficiency for photocatalysis (Saraschandra, Finian, Adhithya, & Sivakumar, 2015; Tahir & Amin, 2015; Sankar & Vijayanand, 2015; Khataee et al., 2015).

2.2.3. Desalination

Due to the limited resources of fresh water, it is likely that in the near future, desalination of sea water will become a major source of fresh water. Conventional desalination technologies like reverse osmosis (RO) membranes are being used but these are costly due to the large amount of energy required. Nanotechnology has played a very important role in developing a number of low-energy alternatives, among which three are most promising. (i) protein–polymer biomimetic membranes, (ii) aligned-carbon nanotube membranes and (iii) thin film nanocomposite membranes (Hoek & Ghosh, 2009). These technologies have shown up to 1000 times better desalination efficiencies than RO, as these have high water permeability due to the presence of carbon nanotube membranes in their structure. Some of these membranes are involved in the integration of other processes like disinfection, deodorizing, de-fouling and self-cleaning. In another approach, zeolite nano-membrane can be used for seawater desalination (Liu & Chen, 2013). Some of these technologies may be introduced in the market place in the near future but scale-up fabrication, practical desalination effectiveness and long-term stability are the most critical challenges to be considered before their successful commercialization (Yan, Sun, & Cheung, 2003). Desalination using nanotechnology with the aspects of carbon nanotubes (Rasel, Eaqub, Sharifah, Seeram, & Zaira, 2014; Rasel et al., 2014), reverse osmosis (Peng, Tom, & Davide, 2011), forward osmosis for seawater and wastewater (Linares et al., 2014), *etc.* have been reviewed earlier. Recently many devices with improved efficiency and performance have been developed — self-sustained webs of polyvinylidene fluoride electrospun nano-fibers (Essalhi & Khayet, 2014); PVA/PVDF hollow fiber composite membrane modified with TiO_2 nanoparticles (Xipeng, Yingbo, Xiaoyu, Yufeng, & Linjia, 2014); novel integrated system coupled with nanofluid-based solar collector (Kabeel & Emad, 2014); zinc oxide micro/nanostructures grafted on activated carbon cloth electrodes (Myint, Salim, & Joydeep, 2014); tubular MFI zeolite membranes (Martin et al., 2012); titanium oxide nanotube/polyethersulfone blend membrane (Abdallah, Moustafa, Adnan, & El-Sayed, 2014); graphene wrapped MnO_2-nanostructures (Ahmed, Nasser, & Hak, 2014); thin film nanocomposite membranes (Arun, Nikolay, & Joseph, 2014); graphene/SnO_2 nanocomposite (El-Deen, Nasser, Khalil, Moaaed, & Hak, 2014), and carbon nanotubes (Goh, Ismail, & Ng, 2013).

Removal of heavy metals

Ligand based nanocoating can be utilized for effective removal of heavy metals as the coated nanoparticles have high absorption tendency. It becomes cost effective as it can be regenerated *in situ* by treatment with bifunctional self-assembling ligand of the previously used nanocoating media. Farmen (2009) used crystal clear technology for water purification in which multiple layers of metal can be bonded to the same substrate using crystal clear technologies. Another strategy for the removal of heavy metals is the use of dendrimer enhanced filtration which can bind cations and anions according to acidity (Diallo, 2009). Nowadays nanomaterials have been widely used to remove heavy metals from water/wastewater due to their large surface area and high reactivity. Metal oxide NPs, including nanosized ferric oxides, manganese oxides, aluminum oxides, titanium oxides, magnesium oxides and cerium oxides, provide high surface area and specific affinity for heavy metal adsorption from aqueous systems. To date, it has become a hot topic to develop new technologies to synthesize metal oxide NPs, to evaluate their capacity to remove the heavy metals under varying experimental conditions. To reveal the underlying mechanism responsible for metal-removal property, several analytical techniques (XAS, ATR-FT-IR, NMR, *etc.*), mathematical models, metal oxide-based nanomaterials such as granular oxides or composite materials are getting employed (Ming et al., 2012). Additionally, humic acid and fulvic acid exist ubiquitously in aquatic environments and have a variety of functional groups which allow them to complex with metal ions and interact with nanomaterials. These interactions can not only alter the environmental behavior of nanomaterials, but also influence the removal and transportation of heavy metals by nanomaterials. Thus, the interactions and the underlying mechanisms involved require specific investigations. Wang-Wang et al. (2014) have given a detailed review on the effects of humic acid and fulvic acid on the removal of heavy metals from aqueous solutions by various nanomaterials, mainly including carbon-based nanomaterials, iron-based nanomaterials and photocatalytic nanomaterials. They have mainly discussed the mechanisms involved in the interactions and evaluated the potential environmental implications of humic acid and fulvic acid to nanomaterials and heavy metals.

2.3. Agro-product processing, storage and distribution

2.3.1. Nanolignocellulosic materials

Recently, nanosized lignocellulosic materials have been obtained from crops and trees which had opened a new market for innovative and value-added nano-sized materials and products. Nano-sized cellulosic crystals have been used as lightweight reinforcement in polymeric matrix (Laborie, 2009). These can be applied in food packaging, construction, and transportation vehicle body structures. Cellulosic nanowhisker production technology from wheat straw has been developed by Michigan Biotechnology Incorporate (MBI) International, and is expected to make biocomposites that could substitute fiber glass and plastics in many applications, including automotive parts. North Dakota State University (NDSU) is currently engaged in a project for the commercialization of this technology (Leistritz et al., 2007). With the applications of food and other packaging, construction, and transportation vehicle body structures, production of nanolignocellulosic materials is the best way for agricultural waste management as it is possible to obtain nanolignocellulosic materials from lignin and cellulose based agricultural waste (Brinchia, Cotana, Fortunati, & Kenny, 2013; Ming-xiong et al., 2014).

2.3.2. Clay nanotubes

Clay nanotubes (halloysite) have been developed as carriers of pesticides for low cost, extended release and better contact with plants, and they might reduce the amount of pesticides by 70–80%, thus reducing the cost of pesticide and also the impact on water streams (Murphy, 2008). The sorptive and electrical behavior of nanocomposites (polylactide and carbon nanotubes/smectite–clay nanocomposites) was studied and it was observed that polylactide nanocomposites are endowed with increased sorption and outstandingly enhanced conductivity (up to 6 or even 9 orders of magnitude) with respect to the pristine polymer (Conductivity $= 1 * 10^{-10}$ S/m) (Saveria et al., 2011). This increased sorptive and increased conductivity properties of nanocomposites may have future applications in selective purification of water and also this property can be applicable in the plant–soil–water interface to increase the ion transport and sorption of nutrients. Hsu

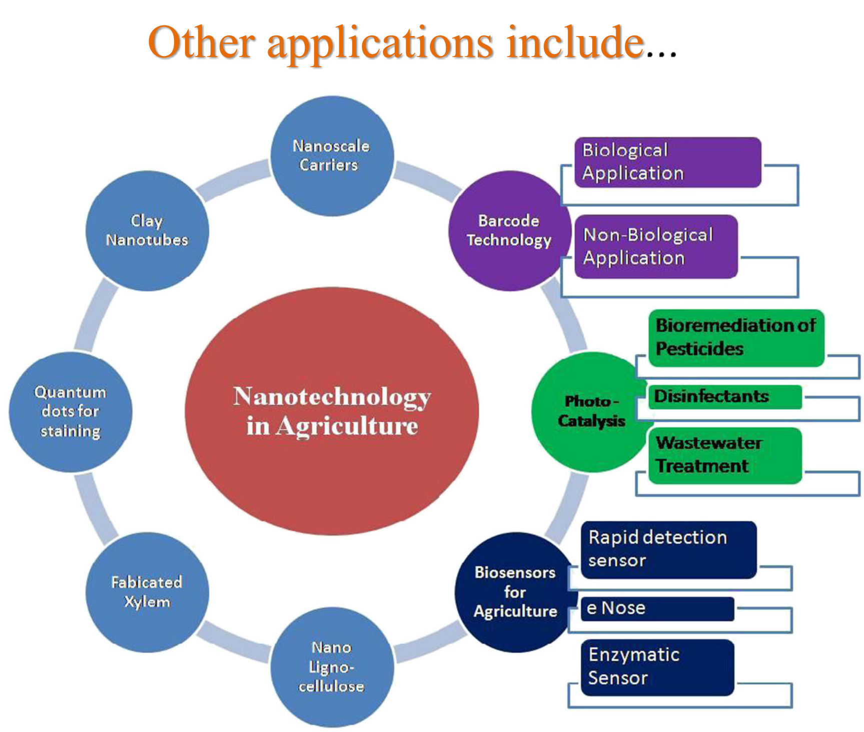

Fig. 1. Diagrammatic representation of nanotechnology application in modern agriculture.

and Jehng (2009) synthesized, characterized and entrapped the carbon nanotubes on clay minerals and used them as a biosensor for glucose and hydrogen peroxide detection. This can have major applications in pre- as well as post-harvested agricultural products and their quality control. Suprakas (2013) has highlighted the tensile strength of clay/carbon nanotubes which may be further used in agricultural fields to provide strength to the crops and protect them from strong winds.

2.3.3. Photocatalysis

One of the processes using NPs is photocatalysis (Blake, 1997). It involves the reaction of catalyst (NPs) with chemical compounds in the presence of light. The electron hole pairs, produced as a result of this reaction, are excellent oxidizing agents and include metal oxides like TiO_2 (Bhatkhande, Pangarkar, & Beenackers, 2001), ZnO (Li & Haneda, 2003), SnO_2 (Ko et al., 2009; Ko, Jung, Lee, Yun, & Jeon, 2013), *etc.*, as well as sulfides like ZnS (Feigl et al., 2010). As the size of particles decreased, surface atoms are increased, resulting in a tremendous increase in chemical reactivity and other physico-chemical properties. So this process can be used for the decomposition of many toxic compounds such as pesticides, which take a long time to degrade under normal conditions (Malato et al., 2002). A detailed research on the trends in the field of photocatalysis using nanomaterials as discussed above reveal that there has been a shift from single nanoparticles to hybrid nanocomposites *e.g.* Ag/$AgVO_3$ one-dimensional hybrid nanoribbons with enhanced performance of plasmonic visible-light photocatalysis (Zhao et al., 2015); fabrication of plasmonic Pt nanoparticles on Ga-doped ZnO nanopagoda array with enhanced photocatalytic activity (Hsien-Ming, Tung-Han, Yang-Chih, Tsong-Pyng, & Jenn-Ming, 2015); PbS quantum dots in ZnO@PbS/graphene oxide have been synthesized for enhanced photocatalytic activity (Xi-Feng et al., 2015); zirconium and silver co-doped TiO_2 nanoparticles for degradation of methyl orange and methylene blue (Saraschandra et al., 2015).

2.3.4. Bioremediation of resistant pesticides

NPs can be used for the bioremediation of resistant and/or slowly degradable compounds like pesticides. These harmful compounds tend to join the positive electron hole pairs; are degraded and converted into non-toxic compounds. Otherwise these harmful compounds enter the food chain and result in serious problems in the body. So NPs can be used for bioremediation and environmental safety (Lhomme, Brosillon, & Wolbert, 2008). Nanotechnology was majorly used in the remediation (nanobioremediation) of uranium, hydrocarbon, groundwater and wastewater, solid waste and heavy metal. Some main nanomaterials involved in nanobioremediation are: nanoiron and its derivatives, nano-sized dendrimers, carbon nanotubes, single enzyme nanoparticles, engineered nanoparticles, *etc.* (Rizwan, Singh, Mitra, & Roshan, 2014; Avinash, Amedea, Nelson, & Mahendra, 2014). Engineered polymeric nanoparticles have been used in bioremediation of hydrophobic contaminants (Tungittiplakorn, Cohen, & Lion, 2005) and soil remediation (Tungittiplakorn, Lion, Cohen, & Kim, 2004). Biogenic uranite nanoparticles have been used for uranium bioremediation (Bargar, Bernier-Latmani, Giammar, & Tebo, 2008). Biologically synthesized nanomaterials from organisms like *Gundelia tournefortii*, *Centaurea virgata*, *Reseda lutea*, *Scariola orientalis*, *Eleagnum angustifolia*, *Bacillus* sp. and *Noaea mucronata* accumulated heavy metals — mainly Cu, Zn, Pb, and Ni (Arvind, Vidya, Bodh, & Sunil, 2011; Avinash et al., 2014; Rizwan et al., 2014).

2.3.5. Disinfectants

The electron hole pair, especially the negative electrons resulting from the excitation of NPs, can also be used as a disinfectant for bacteria, as when bacteria make contact with NPs, the excited electrons are transfered into their bodies, resulting in the removal of bacteria from the object concerned as in fruit packaging and food engineering (Melemeni, Stamatakis, Xekoukoulotakis, Mantzavinos, & Kalogerakis, 2009). Comparatively NPs are better disinfectants than chemical disinfectants *e.g.* sodium hypochlorite (NaClO) and phenol (C_6H_5OH) *etc.* (Karthik, Rafael, Zhiping, Sajid, & Jingbo, 2011). Wei, Chengtie, Pingping, Yinghong, and Yin (2012) have concluded that the porous Ca–Si based nanospheres may be developed into a new intra-canal disinfectant-carrier for infected canal treatment. Nano-disinfectant in the form of film/layer has shown improved antimicrobial activity for *Salmonella* and *Staphylococcus* spp. (Carla, Davide, Pietro, Lucio, & John, 2012; Hans, Kim, Jos, & Sigrid, 2012; Kumar & Ting, 2013; Nithila et al., 2014).

2.4. Quality control with nano-sensors

2.4.1. Nanobarcode technology

In our daily life, identification tags have been applied in wholesale agriculture and livestock products. Due to their small size, NPs have been applied in many fields ranging from advanced biotechnology to agricultural encoding. Nanobarcodes have been applied in multiplexed bioassays and general encoding because of their possibility of formation of a large number of combinations. The UV lamp and optical microscope are used for the identification of micrometer-sized glass barcodes which are formed by doping with rare earth containing a specific type of pattern of different fluorescent materials. The particles to be utilized in nanobarcodes should be easily encodeable, machine-readable, durable, sub-microsized taggant particles. For the manufacture of these nanobarcode particles, inert metals (gold, silver, *etc.*) are electroplated into templates defining particle diameter, and then the resulting striped nanorods from the templates are released. These nanobarcodes have biological as well as non-biological applications (Mathew, Marie-Pierre, & Kristiina, 2009). Cost effective nanobarcode technology development is a major challenge for the researchers — this can be concluded based on the fact that a total of 18 documents were found on the Scopus indexed article database (SIAD). Out of the 18 articles, notes (1 in number), conference papers (6 in number), review articles (2 in number) and only 9 research articles were available in the last 10 years by the keyword "nanobarcode" (SIAD, 2014). Similarly, only 32 articles are present in the SciFinder® database with the same keyword. After refining it yearwise, none of these articles were found for 2014; only one article in duplicate was found *i.e.* authored by Han, Hong, Kim, Sung, and Lee (2013) which have been discussed earlier; similarly, 3 articles have been found for the year 2012 but none of them have described the application of nanobarcodes in the agricultural field (SciFinder, 2014). This shows that the development of nanobarcode technology for agricultural application is one of the thrust areas.

2.4.2. Biological applications of nanobarcodes

Nanobarcodes have been used as ID tags for multiplexed analysis of gene expression and intracellular histopathology. Improvement in the plant resistance against various environmental stresses such as drought, salinity and diseases has only been possible through advancement in the field of biotechnology at the nanoscale. In the near future, more effective identification and utilization of plant gene trait resources are expected to introduce rapid and cost effective capability through advances in nanotechnology-based gene sequencing (Branton et al., 2008). Nanobarcodes can also be used for cost-effective detection of pathogens from food products (Han et al., 2013).

2.4.3. Non-biological applications of nanobarcodes

Nanobarcodes serve as uniquely identifiable nanoscale tags and have been applied for non-biological applications such as those for authentication or tracking in agricultural food and animal husbandry products. This nanobarcode technology will enable us to develop new auto-ID technologies for the tagging of items that were previously not available with conventional barcodes (Branton et al., 2008).

2.4.4. Quantum dots (QDs) for staining bacteria

There are numerous bacteria which are responsible for many human diseases like tetanus, typhoid fever, diphtheria, syphilis, cholera, food-borne illness, leprosy and tuberculosis. As a remedial process, we need to detect bacteria using staining dye. To stain bacteria, the most commonly used biolabels are organic dyes, but these are expensive and their fluorescence quenches with time. So the need of the hour is to find durable and economical alternatives. Fluorescent labeling by quantum dots (QDs) with bio-recognition molecules has been discovered through the recent developments in the field of luminescent nanocrystals. QDs are better than conventional organic fluorophores (dyes) due to their more efficient luminescence, narrow emission spectra, excellent photostability, symmetry and tunability according to particle size and material composition. By a single excitation light source, they can be excited to all colors (Warad, Ghosh, Thanachayanont, Dutta, & Hilborn, 2004). *Bacillus* bacteria labeled with NPs consisting of ZnS and Mn^{2+} capped with biocompatible 'chitosan' gave an orange glow when viewed under a fluorescence microscope. For the detection of *E. coli* O157:H7, QDs were used as a fluorescence marker coupled with immune magnetic separation (Su & Li, 2004). For this purpose, magnetic beads were coated with anti-*E. coli* O157 antibodies to selectively attach target bacteria, and biotin-conjugated anti-*E. coli* antibodies to form sandwich immune complexes. QDs were labeled with the immune complexes *via* biotin–streptavidin conjugation after magnetic separation.

2.4.5. Biosensors

A variety of characteristic volatile compounds are produced by microorganisms that are useful as well as harmful to human beings *e.g.*, fermentation makes use of yeasts while alcohol is produced as a by-product when bacteria eat sugar. The most common causal organisms of food rotting are bacteria. Foul odor is a clear indication of food degradation which may be detected by visual and nasal sensation, but sometimes it may be impractical and a further cause of poisoning. Therefore, it is more sensible to use rapid detection biosensors for the detection of these odors (Compagnone, McNeil, Athey, Dillio, & Guilbault, 1995). The future application of nano-biosensors recently developed by Xiqi et al. (2014) and Zhang et al. (2014) is described above in this review. Nano-biosensors are getting applications in different industries other than food and agriculture but recently many sensors have been developed after considering its importance. A detailed review on this has been done by Teresa (2013).

2.4.6. Rapid detection biosensors

These instruments are able to reduce the time required for lengthy microbial testing and immunoassays. Applications of these instruments include detection of contaminants in different bodies such as water supplies, raw food materials and food products (Compagnone et al., 1995). Recently, nanobiosensors are developed for rapid detection of IgG and metabolites (Labroo & Cui, 2014; Türkoğlu, Yavuz, Uzun, Akgöl, & Denizli, 2013). Considering microbial contamination, a device (electrogenerated chemiluminescence immunosensor) has been found to use Fe_3O_4@Au to detect *Bacillus thuringiensis* (Jianping, Qian, Xiaoping, & Zaibin, 2013). By keeping food and agricultural safety into consideration a biosensor using chemiluminescence and electrochemiluminescence immunoassay has been found to detect botulinum neurotoxin serotypes A and B (Cheng & Stanker, 2013). While considering aquaculture — to measure volatile amine levels in fish, an optical fiber-based micro-analyzer was designed. This is a future aspect into developing such nano-biosensors instead of micro-analyzers (Silva, Ferreira, Freitas, Rocha-Santos, & Duarte, 2010).

2.4.7. Enzymatic biosensors

Enzymes can act as a sensing element as these are very specific in attachment to certain biomolecules. According to Patel (2002), enzymatic biosensors are classified into four groups on the basis of immobilization surface as (i) controlled-pore glass beads with an optical transducer element, (ii) polyurethane foam with a photo-thermal transducer element, (iii) ion-selective membrane with either a potentiometric or an amperometric transducer element and (iv) screen-printed electrode with an amperometric transducer element.

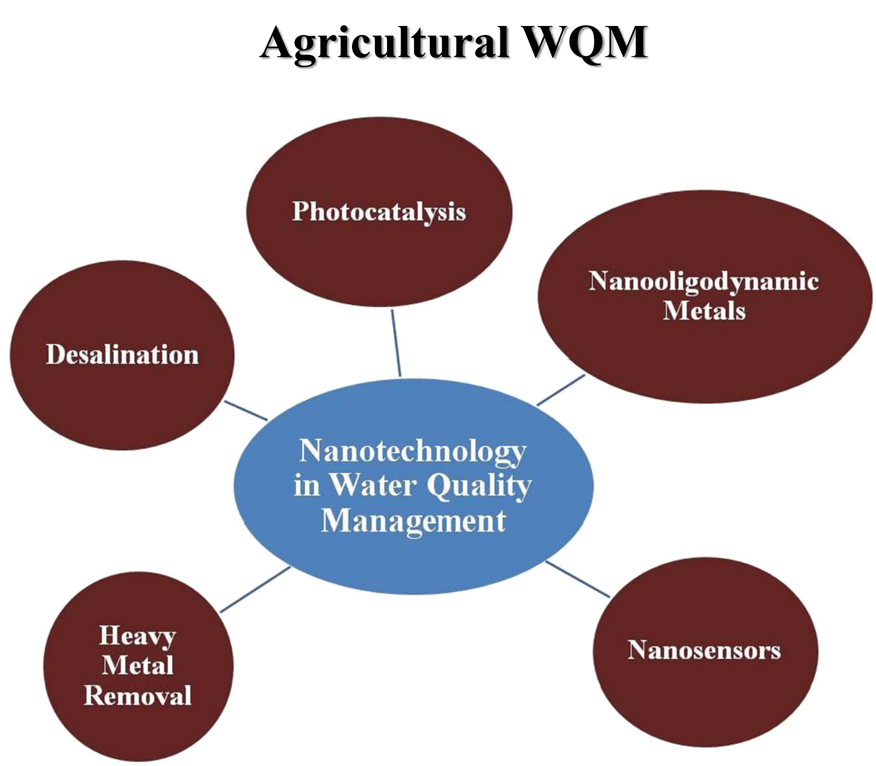

Fig. 2. Diagrammatic representation of nanotechnological aspects in water quality management.

2.4.8. Electronic nose (E-nose)

It is a device whose operation is based on the human nose and is used to identify different types of odors; it uses a pattern of response across an array of gas sensors. It can identify the odorant, estimate the concentration of the odorant and find characteristic properties of the odor in the same way as might be perceived by the human nose. It mainly consists of gas sensors which are composed of nanomaterials *e.g.* ZnO nanowires (Hossain, Ghosh, Boontongkong, Thanachayanont, & Dutta, 2005; Sugunan, Warad, Thanachayanont, Dutta, & Hofmann, 2005). ZnO nanorods were used to develop the electronic nose which can detect impurities from a mixture of vapors (Ko et al., 2013). Their resistance changes with the passage of a certain gas — generates a change in electrical signal that forms the fingerprint pattern for gas detection. This pattern is used to determine the type, quality and quantity of the odor being detected. There is also an improved surface area which helps in better absorption of the gas.

2.4.9. Gold NPs

Gold NPs, commercially used as rapid testing arrays for pregnancy tests and biomolecule detectors, are based on the fact that the color of these colloids depends on the particle size, shape, refractive index of the surrounding media and separation between the NPs. A quantifiable shift in the surface plasmon response (SPR) absorption peak results is due to a small change in any of these parameters. NPs can attach to specific molecules by using a capping agent for stabilizing gold NPs. These specific molecules get adsorbed on the surface of these NPs and change the effective refractive index of the immediate surroundings of the NPs (Nath & Chilkoti, 2004). A few NPs will be adsorbed if the detecting molecules (bio-macromolecules) are larger than the gold NPs and result in the formation of lumps after agglomeration. Ultimately, the color of gold NPs is changed due to a shift in SPR that results from the reduction of particle spacing. These properties provide a great opportunity to use gold NPs for biosensor development. In the field of pharmaceutical science and other biomedical fields many gold-nanoparticle-based biosensors have been already developed for detection of enzyme activity — the same should be researched in the field of food, agriculture and WQM (Eliza & Dusica, 2013).

2.4.10. Wireless nanosensors for WQM

Crop growth and field conditions like moisture level, soil fertility, temperature, crop nutrient status, insects, plant diseases, weeds, *etc.* can be monitored through advancement in nanotechnology. This real-time monitoring is done by employing networks of wireless nanosensors across cultivated fields, providing essential data for agronomic intelligence processes like optimal time of planting and harvesting the crops. It is also helpful for monitoring the time and level of water, fertilizers, pesticides, herbicides and other treatments. These processes are needed to be administered given specific plant physiology, pathology and environmental conditions and ultimately reduce the resource inputs and maximize yield (Scott & Chen, 2003). Scientists and engineers are working to develop such strategies that can increase the efficiency of water usage in agricultural productions. Drip irrigation is one such measure to increase efficient water usage. This has moved precision agriculture to a much higher level of control in water usage, ultimately leading towards the conservation of water. More precise water delivery systems are likely to be developed in the near future. These systems are critical for water storage, *in situ* water holding capacity, water distribution near roots, water absorption efficiency of plants, encapsulated water released on demand, and interaction with field intelligence through distributed nano-sensor systems (Cross et al., 2009). Sensing and detection of various contaminants in water at nanoscale under laboratory and field conditions have remained a hot issue over the last decade. In the near future, nanotechnology-based techniques will help in developing many new technologies that will have better detection and sensing ability (Chen & Yada, 2011). ZigBee (a mesh networking standard) is a very good example in this regard. ZigBee is a low cost wireless mesh networking standard which utilizes low power. It has given the concept of 'Smart Fields' and 'SoilNet'. It consists of one or more sensors for environmental data (temperature, humidity, *etc.*), a signal conditioning block, a microprocessor/microcontroller with an external memory chip and a radio module for wireless communication between the sensor nodes and/or a base station. It can be used for the identification and monitoring of pests, drought or increased moisture levels in order to counterbalance their adverse effects on crop production (Kalra, Chechi, & Khanna, 2010). Through this wireless sensor technology with sensitivity to detect nanoscale materials, plant viruses and the level of soil nutrients can be controlled, as the plant surfaces can be changed at nanoscale with specific proteins. Wireless network sensor technology can also be used for monitoring the optimal conditions for mobile biomolecules in plants (Allah, 2012).

3. Nanoresearch in the food supply chain

Nanostructured materials exhibit unique physicochemical properties that open windows of opportunities for the creation of new, high performance materials, which will have a critical impact on food manufacturing, packaging and storage. Currently, nanotechnology in food production is focused on the development of nano-sized food ingredients and additives, delivery systems for bioactive compounds and innovative food packaging. The applications of NPs and nanotechnologies boost the researchers and industries alike. It has been noticed recently, that the development of smart delivery systems of nutrients or other food ingredients, rapid sampling of biological and chemical contaminants and nanoencapsulation of nutraceuticals for controlled release, water purification and cell-wall rupture for pathogenic bacteria in agri-food samples or water. Though several applications of nanotechnology in food have recently been reported, only some examples will be explored in the present scenario (Sastry, Rashmi, & Rao, 2010; Ranjan et al., 2014; Kalpana, Rashmi, Rao, & Ilyas, 2010; Sastry, Rashmi, & Rao, 2011).

3.1. Food processing

Food industries are always searching for new, cheaper methods to produce and preserve food. The realm of nanotechnology offers many options in food manufacture, encapsulation, nanofiltration, *etc.* Processing helps to maintain the nutritional quality of the food or to modify the food matrix, according to the consumer demands. Functional ingredients added for food fortification (including vitamins, antimicrobials, antioxidants, probiotics, prebiotics, peptides and proteins, carotenoids, omega fatty acids, flavorings, colorants and preservatives) are not administrated directly in their pure form, but are sometimes incorporated into the delivery system (*e.g.* nanostructures) (Elliott & Ong, 2002). However, these active molecules are often degraded in the processing steps and offer poor bioavailability. Nanoencapsulation and nanoemulsion formulations can be utilized so that functional food ingredients can be incorporated, absorbed, or dispersed in nanostructures. Nanostructures of inorganic materials have also been studied as a coating material to provide a moisture or oxygen barrier (e.g. silicon dioxide (E551), magnesium oxide (E530), titanium dioxide (E171), and antibacterial 'active' coating, especially silver) (Chaudhry & Groves, 2010). Different products have been developed based on Nanoclusters™ system, such as Slim Shake Chocolate, which incorporates silica nanoparticles that are coated with cocoa to enhance the chocolate flavor. NanoCluster™, from RBC Life Sciences® Inc. (Irving, TX, USA), is another such delivery system for food products (Ranjan et al., 2014).

New food products containing nanostructures have been introduced or are being currently developed for different purposes (Chaudhry et al., 2008; Weiss et al., 2008; Luykx, Peters, Van, & Bouwmeester, 2008; Rao & McClements, 2012): (i) to protect nutraceuticals against degradation during manufacturing, distribution and storage, improving their stability, (ii) to enhance the bioavailability of poorly soluble functional food ingredients (e.g. hydrophobic vitamins) thus improving their nutritional value, (iii) to increase food shelf life by protecting it from oxygen and water (Leclercq, Harlander, & Reineccius, 2009), (iv) to produce low fat, low carbohydrate or low calorie products (*e.g.* mayonnaise, spreads and ice creams), (v) to optimize and modify the sensory characteristics of food products creating new consumer sensations (*e.g.* texture, consistency, development of new taste or taste masking, flavor enhancement, color alteration) and (vi) to control functional food ingredient delivery (*e.g.* flavor, nutrient). Additionally, encapsulation also aids in controlled release of active ingredients wherein gastrointestinal retention time can be prolonged and the site of release of active ingredient can be adjusted according to the need (Medina, Santos-Martinez, Radomski, Corrigan, & Radomski, 2007; Krasaekoopt, Bhandari, & Deeth, 2003; Li et al., 2008). Nanotechnology can also be employed to solubilize lipophilic ingredients such as carotenoids, phytosterols, and antioxidants in water so as to disperse in water or fruit drinks (Chen, Weiss, & Shahidi, 2006; Chen, Remondetto, & Subirade, 2006). Lycopene nanostructures (particle size of 100 nm, US5968251) have been developed and accepted as GRAS substance by the Food and Drug Administration (FDA). The water-dispersible lycopene nanostructures can be added to soft drinks to provide color and health benefits (Limpens et al., 2006). Lycopene has been included in other products such as baking mixtures and blancmanges (Chaudhry & Groves, 2010). Astete, Sabliov, Watanabe, and Biris (2009) reported the use of b-carotene, an oil-soluble pigment to color water-based foods.

Certain ingredients with high nutritional value are prone to degradation due to processing steps. For example, ω-3 polyunsaturated fatty acids are easily oxidized; so they require both stabilization procedures and protection against deterioration factors (Lavie, Milani, Mehra, & Ventura, 2009; Ruxton, Reed, Simpson, & Millington, 2004). Zimet, Rosenberg, and Livney (2011) developed casein nanostructures and reformed casein micelles that showed a remarkable protective effect against docosahexaenoic acid oxidation up to 37 days at 4 °C. BioDelivery Sciences International has developed Bioral™ nanocochleate nutrient delivery system, which is a phosphatidylserine carrier (~50 nm), derived from soya bean (GRAS status). This system has been used for protecting micronutrients and antioxidants from degradation during manufacture and storage (Chaudhry & Groves, 2010). Recently, natural dipeptide antioxidants (e.g. L-carnosine) have been used as biopreservatives in food technology. However, their direct application in food is not possible as they are unstable and may lead to proteolytic degradation and a potential interaction of peptide with food components. Maherani, Arab-Tehrany, Kheirolomoom, Cleymand, and Linder (2012) have successfully encapsulated these natural antioxidant peptides by nanoliposomes to overcome the limitations related to the direct application in food. Coenzyme Q10 (CoQ10) has low oral bioavailability, which does not allow it to reach its therapeutic concentration easily. Ankola, Viswanad, Bhardwaj, Ramarao, and Kumar (2007) demonstrated the potential of nanotechnology in improving the therapeutic value of molecules like CoQ10, facilitating its usage as a first-line therapeutic agent for prophylaxis of consumers for better health. Biodegradable polymeric nanostructures based on poly(lactide-co-glycolide) (PLGA), using quaternary ammonium salt didodecyldimethyl ammonium bromide as a stabilizer are also developed for the purpose.

Wen, Decory, Borejsza-Wysocki, and Durst (2006) described the applications of liposomes in oral delivery of functional food ingredients like proteins, enzymes, flavors, and antimicrobial compounds. The entrapment of proteolytic enzymes in liposomes for cheese production (Mozafari et al., 2006; Walde & Ichikawa, 2001), can reduce the production time to half without compromising flavor and texture. Similarly, Wu, Luo, and Wang (2012) have recently demonstrated that the entrapment of essential oils within zein nanostructure allows their dispersion in water, enhancing their potential for use as antioxidant and antimicrobial agents in food preservation. Tang et al. (2013) developed self-assembled nanostructures composed of chitosan and an edible polypeptide, poly(γ-glutamic acid), for oral delivery of tea catechins, which can be used as food additives for drinks, foods and dietary supplements. Likewise, food additives can be entrapped into nanostructures to mask the taste and odor of fish oil which may be further added to bread for health benefits and live probiotic microbes can be added to promote gut functions (Chaudhry et al., 2008). With the future aspect of facilitating the rational development of zein-based nanoscale delivery systems for the transportation of hydrophobic bioactive compounds with ideal surface morphology and functionalities for food and pharmaceutical applications, many works have been done to synthesize zein, casein and gelatine based nanoparticles (Chen, Ran, & Liu, 2013; Ye & Harte, 2013; Ye, Ran, & Jun, 2014; Ye, Ran, Lia, & Wang, 2013; Wang et al., 2014; Xin, Anjun, Ran, Yuemeng, & Wenhang, 2015).

Nanoemulsions reduce the need for stabilizers as they will protect against breakdown and separation of food (Cushen, Kerry, Morris, Cruz-Romero, & Cummins, 2012) and can thus significantly reduce the quantity of fat needed. The products of such nanoemulsions are as 'creamy' as conventional food products, with no compromise on the mouth feel and flavor. The use of zein nanostructures, a major protein found in corn, has also been explored as a vehicle of flavor compounds and essential oils (*e.g.* thymol and carvacrol), because they have the potential to form a tubular network resistant to microorganisms (Sozer & Kokini, 2009; Wu et al., 2012). Another nanostructure proposed to encapsulate nutraceuticals (e.g. vitamins) or to mask disagreeable flavor/odor compounds is the α-lactalbumin nanotube, which can be obtained from milk protein (Graveland-Bikker & De-Kruif, 2006; Srinivas et al., 2010). Based on the origin of these nanostructures, they can be regarded as food grade, which makes their common application in the entrapment of functional food ingredients easier (Cushen et al., 2012).

3.1.1. Nanofiltration

Nanofiltration is a method in which low-molecular mass solutes can be separated from a liquid medium. Nanofiltration membranes have a high permeability for (monovalent) salts (*e.g.* NaCl or KCl) and a very low permeability for organic compounds (*e.g.* lactose, proteins, and urea). The separation mechanisms are determined by complex steric and electrical effects or electroneutrality principle such as that in the Donnan effect (Xu & Spencer, 1997). The nanofiltration membrane behavior is influenced by the feed solution characteristics (Mohammad & Takriff, 2003) and by the membrane material properties (Minhalma, Magueijo, Queiroz, & Pinho, 2007; Li, Mahendra, et al., 2008) *i.e.* the membrane performance depends mainly on three parameters namely; effective pore radius, effective ratio of membrane thickness to porosity, and the effective charge density. This method is very attractive for industrial applications in the food and pharmaceutical industries especially as a purification step or to obtain certain solutes. In the dairy industry nanofiltration is used to improve the quality of the products (Cuartas-Uribe, Alcaina-Miranda, Soriano-Costa, & Bes-Pia, 2007), and to separate mineral salts from lactose, after removing the proteins by ultrafiltration.

Nanofiltration has been successfully applied in drinking water treatment plants (Hofman, Beerendonk, Folmer, & Kruithof, 1997; Bonne, Beerendonk, vanderHoek, & Hofman, 2000; Cyna, Chagneau, Bablon, & Tanghe, 2002; Carla, José, & Paula, 2013). It has been reported to be directly used in combination with powdered activated carbon to remove effluent organic matter from municipal wastewater (Kazner et al., 2008, Cuartas-Uribe et al., 2007). Using nanofiltration, a purity of over 91% and an overall yield of 71% which is much higher than the conventional methods, can be achieved in such cases (Vegas et al., 2008).

3.2. Food packaging

Food industries are always searching for new, cheaper methods to produce and preserve food. Recent trends in food packaging are related to nanoreinforcement, nanocomposite active packaging and nanocomposite smart packaging (Fig. 3). Polymers have replaced conventional materials (glass, ceramics, metals, paper and board) in food packaging

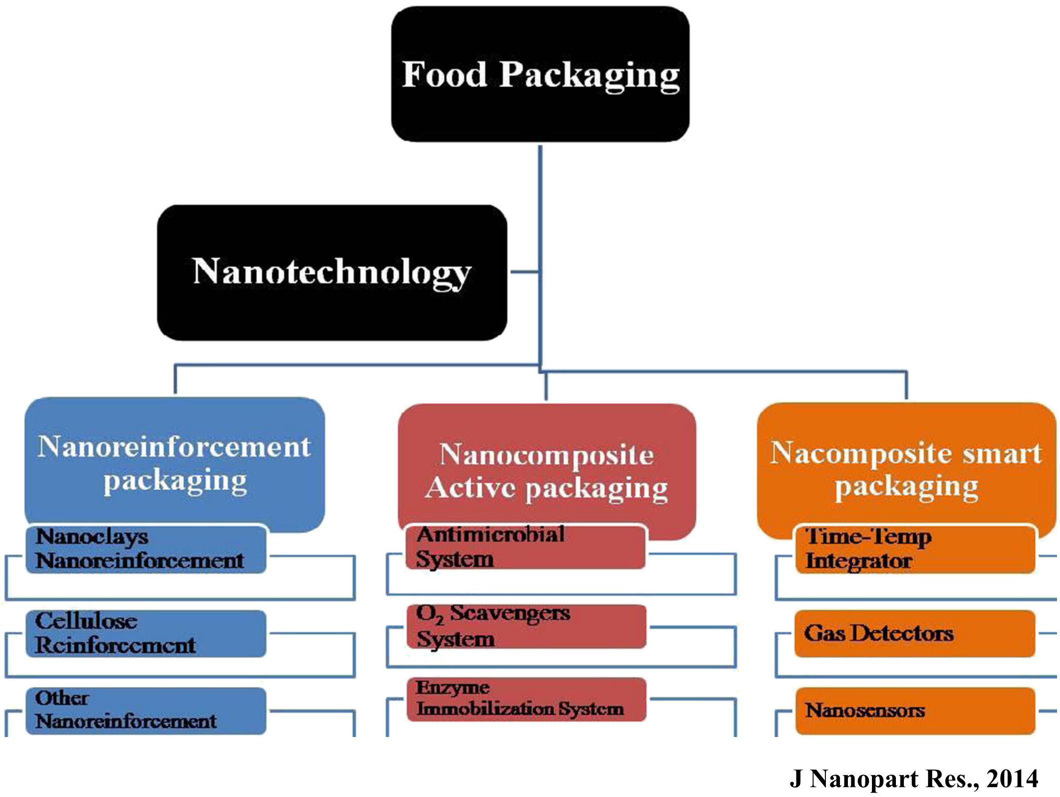

Fig. 3. The research trends of food packaging with the help of nanotechnology.
Courtesy: Ranjan et al. (2014).

owing to their functionality, light weight, low cost and ease of processability. However, their strength and capability to resist deformation are lower as compared to metals and ceramics (Jordan et al., 2005). Furthermore, their inherent permeability to gases and vapors is another limiting property in food packaging (Arora & Padua, 2010). Nanoreinforcement techniques are used to increase viability and tensile strength by filling the gaps of packaging materials. Polymer nanocomposites usually have much better polymer/filler interactions than the usual composites (Ludueña, Alvarez, & Vasquez, 2007). Nanoreinforcement using nanoclays, cellulose, *etc.* gives extra tensile strength to food packets. Nanocomposite active packaging integrates many useful systems (*e.g.* antimicrobial, oxygen scavenging and enzyme immobilization systems) along with the food packets.

With the recent advancement in nanotechnology, the correlation of material properties with filler size has become a point of great interest as they enhance composite performance by improving the mechanical strength, thermal stability, and barrier properties in comparison to virgin polymer matrix (Goettler, Lee, & Thakkar, 2007). The packaging industry has recently focused its attention on nanoclay particulates due to their easy availability, low cost, easy processability and good performance. Carbon based materials like carbon nanotubes and graphene nanosheets are also being developed (Arora & Padua, 2010).

3.2.1. Nanoclay reinforcement

In the last two decades, a new emerging class of clay filled polymers, called polymer clay nanocomposites (PCNs) has been developed. In contrast to the typical tactoid structure of microcomposites (conventional composites) in which the polymer and the clay tactoids remain immiscible (Ludueña et al., 2007; Alexandre et al., 2009), the interaction between layered silicates and polymers may produce two types of nanoscale composites, namely: intercalated nanocomposites, which result from the penetration of polymer chains into the interlayer region of the clay, producing an ordered multilayer structure with alternating polymer/inorganic layers (Weiss, Takhistov, & McClements, 2006), and exfoliated nanocomposites, which involve extensive polymer penetration, with the clay layers delaminated and randomly dispersed in the polymer matrix (Ludueña et al., 2007).

3.2.2. Cellulose nanoreinforcements

Ranjan et al. (2014) have mentioned in their review that cellulose nanoreinforcements (CNRs) are interesting materials for the preparation of low cost, lightweight, and high-strength nanocomposites (Podsiadlo et al., 2005). Cellulose chains are synthesized in living organisms (mainly plants) as microfibrils (or nanofibers), which are bundles of elongated molecules (with 2–20 nm in diameter and micrometric in length) stabilized by hydrogen bonds (Mattoso et al., 2009; Ranjan et al., 2014). Each microfibril, formed by elementary fibrils, has crystalline and amorphous regions. The crystalline parts, which may be isolated by procedures such as acid hydrolysis, are the nanocrystals or nanowhiskers whose aspect ratios are related to the origin of the cellulose and processing conditions (Azizi, Alloin, & Dufresne, 2005).

3.2.3. Other nanoreinforcements

Carbon nanotubes consisting of a one-atom thick single-wall nanotube, or a number of concentric tubes called multiwalled nanotubes, have extraordinarily high aspect ratios and elastic modulus (Zhou, Shin, Wang, & Bakis, 2004). Several polymers such as polyethylene naphthalate (Kim, Il-Han, & Hong, 2008), polyvinyl alcohol (Chen & Evans, 2005), polypropylene (Prashantha et al., 2009), and a polyamide (Zeng et al., 2006) have been found to have their tensile strength/modulus improved by addition of carbon nanotubes. A great number of polymers such as silica NPs ($nSiO_2$) have been reported to improve tensile properties of polypropylene (Vladimiriov, Betchev, Vassiliou, Papageorgiou, & Bikiaris, 2006), starch (Xiong, Tang, Tang, & Zou, 2008), starch/polyvinyl alcohol (Tang & Liu, 2008), decreasing water absorption by starch (Tang & Liu, 2008; Xiong et al., 2008) and improving oxygen barrier of polypropylene (Vladimiriov et al., 2006). Jia, Li, Cheng, Zhang, and Zhang (2007) prepared nanocomposites of polyvinyl alcohol with $nSiO_2$ by radical copolymerization of vinyl silica NPs and vinyl acetate. The nanocomposites improved thermal and mechanical properties when compared to the pure polyvinyl alcohol, due to strong interactions between $nSiO_2$ and the polymer matrix *via* covalent bonding.

3.2.4. Nanocomposite active food packaging

Unlike conventional food packaging, an active food packaging may not only act as a passive barrier but also interact with the food in some desirable way like by releasing desirable compounds such as antimicrobial or antioxidant agents, or by removing some detrimental factor (such as oxygen or water vapor). The consequences of such interactions are usually related to improvements in food stability. Some of the main examples of food packaging systems include the following.

3.2.5. Antimicrobial systems

Antimicrobial systems are fast emerging as viable solutions due to their ability to control the growth of pathogenic and spoilage-causing organisms on food surfaces. The higher surface to volume ratio of nanoscale materials in relation to microscale products enables such systems to attach more copies of microbes and cells (Luo & Stutzenberger, 2008). Nanoscale materials have been investigated for antimicrobial activity as growth inhibitors (Cioffi et al., 2005), killing agents (Huang et al., 2005; Kumar & Münstedt, 2005), or antibiotic carriers (Gu, Ho, Tong, Wang, & Xu, 2003).

Though silver is known for its toxicity towards an array of microorganisms (Liau, Read, Pugh, Furr, & Russell, 1997), it also offers some advantages such as higher temperature stability and low volatility (Kumar & Münstedt, 2005). Adhesion to the cell surface, degradation of lipopolysaccharides and formation of "pits" in the membranes, increasing permeability (Sondi & Salopek-Sondi, 2004), penetration inside bacterial cell, damaging DNA (Li, Mahendra, et al., 2008) and releasing antimicrobial Ag^{+} ions by dissolution of silver nanoparticles (Morones et al., 2005), *etc.* are mechanisms of action for its antimicrobial activity. Silver NPs have also been reported to absorb and decompose ethylene, which may contribute to their effects on extending shelf life of fruits and vegetables (Li et al., 2009).

Nanostructured calcium silicate (NCS) was used by Johnston (2010) to adsorb Ag^{+} ions from a solution. The resulting NCS–Ag complex exhibited effective antimicrobial activity at desirably low levels of silver down to 10 mg/kg, and was feasible for incorporation into food packaging as an antimicrobial agent. Titanium dioxide (TiO_2) is widely used as a photocatalytic disinfecting material for surface coatings (Fujishima, Rao, & Tryk, 2000). TiO_2 photocatalysis, which promotes peroxidation of the phospholipids present in microbial cell membranes (Maness et al., 1999), has been used to inactivate food-related pathogenic bacteria (Robertson, Robertson, & Lawton, 2005, Chawengkijwanich & Hayata, 2008). TiO_2-coated films exposed to sunlight can inactivate fecal coliforms in water (Gelover, Gómez, Reyes, & Leal, 2006; Reddy, Venugopal, & Subrahmanyam, 2007); doping TiO_2 with silver improves visible light absorbance of TiO_2 (Anpo et al., 2001; Cheng, Li, Pavlinek, Saha, & Wang, 2006), and increases its photocatalytic activity under UV irradiation (Choi, Termin, & Hoffmann, 1994). The antibacterial activity of chitosan NP may be due to interactions between the positively charged chitosan and the negatively charged cell membranes (Qi, Xu, Jiang, Hu, & Zou, 2004) thereby increasing membrane permeability and eventually causing rupture and leakage of the intracellular material.

Carbon nanotubes have also been reported to have antibacterial properties. Direct contact with aggregates of carbon nanotubes has been demonstrated to kill *E. coli*, possibly because the long and thin nanotubes puncture microbial cells, causing irreversible damages and leakage of intracellular material (Kang, Pinault, Pfefferle, & Elimelech, 2007). On the other hand, there are studies suggesting that carbon nanotubes may also be cytotoxic to human cells, at least when in contact with skin (Monteiro-Riviere, Nemanich, Inman, Wang, & Riviere, 2005) or lungs (Warheit et al., 2004). Once present in the food packaging material, the nanotubes might eventually migrate into food. Thus, it is mandatory to know any eventual health effects of ingested carbon nanotubes.

3.2.6. O_2 scavengers

Oxygen (O_2) participates in several forms of food deterioration like browning reactions and rancid flavors. The incorporation of O_2 scavengers into food packaging systems can maintain very low O_2 levels. Oxygen scavenger films were successfully developed by Xiao-e, Green, Haque, Mills, and Durrant (2004) by adding TiO_2 NPs to different polymers, but as TiO_2 acts by a photocatalytic mechanism, its major drawback is the requirement of UVA light (Mills, Doyle, Peiro, & Durrant, 2006).

3.2.7. Enzyme immobilization systems

Enzymes have a variety of applications in the food industry. However, their sensitivity to processing conditions and/or to enzyme inhibitors can sometimes restrict the applicability of the direct enzyme addition to foods. Immobilization is usually an effective way to improve stability of enzyme to pH and temperature, resistance to proteases and other denaturing compounds, as well as to provide an adequate environment for their repeated use or controlled release (Lopez-Rubio, Gavara, & Lagaron, 2006). Enzyme immobilization has been considered for packaging applications (Soares & Hotchkiss, 1998). The incorporation of enzymes like lactase or cholesterol reductase to packaging materials could increase the value of food products and answer the needs of consumers with enzyme deficiencies (Fernández, Cava, Ocio, & Lagaron, 2008). Nanoscale enzyme immobilization systems would have enhanced performance when compared to conventional ones because of their much higher surface contact area and mass transfer rate (Fernández et al., 2008). Approaches dealing with enzyme adsorption into nanoclays incorporated to polymers might be expected (Rhim & Ng, 2007), since NCs have a high affinity for protein adsorption, and have been reported to be efficient enzyme carriers (Gopinath & Sugunan, 2007). SiO_2 nanoparticles have been modified to immobilize glutamate dehydrogenase and lactate dehydrogenase (Qhobosheane, Santra, Zhang, & Tan, 2001), which have shown excellent enzyme activity upon immobilization.

3.3. Nutraceutical delivery

Nano-food/supplements or nutraceuticals are available as delivery systems in the market, mainly as regulatory peptides from plants, nano-droplets/-clusters and nano-emulsions (Chen, Weiss, et al., 2006; Graveland-Bikker & De-Kruif, 2006; Mozafari et al., 2006). Many of these nano-delivery systems (Letchford & Burt, 2007; Taylor, Davidson, Bruce, & Weiss, 2005) result in efficient delivery of bioactive compounds and thus helps to increase the bioavailability. Valid studies on relative bioavailability comparing these products with similar non-nano-food products are lacking (Bouwmeester et al., 2009). For effective delivery systems, the encapsulated compounds should be delivered to the target sites, should be maintained at a suitable concentration for prolonged time periods and the degradation should be prevented; which has been achieved after various modifications by researchers (Chen, Remondetto, & Subirade, 2006b; Medina et al., 2007; Bouwmeester et al., 2009). NPs and nanospheres allow better encapsulation, improved stability and solubility, and release efficiency than traditional encapsulation systems. It can be noted that, although NPs present different release profiles compared to microparticles, for instance but many times NP release is too fast, so MPs are chosen. Therefore, based on the applications of release the NPs of microparticles should be selected (Bodmeier, Chen, & Paeratakul, 1989; Roy, Mao, Huang, & Leong, 1999; Letchford & Burt, 2007; Taylor et al., 2005). A few of such delivery systems are discussed below.

3.3.1. Lipid-based nano-delivery systems

The main lipid-based nano-encapsulates which can widely be used in food/supplements are nanoliposomes, archaeosomes (at an experimental stage) and nanocochleates (Mozafari et al., 2006; Sastry, Shrivastava, & Rao, 2013). Their unique size and hydrophilic/hydrophobic properties enable them to entrap, deliver, and release both water-soluble and lipid soluble materials (Mozafari et al., 2006; Mozafari, Johnson, Hatziantoniou, & Demetzos, 2008; Rao & McClements, 2012). A very stable and precise delivery system is represented by "cochleates" — a phospholipid-divalent cation precipitate composed of naturally occurring materials, developed and patented by BioDelivery Sciences International Inc., Newark, NJ (Moraru et al., 2003; Ranjan et al., 2014).

Another system – nanocochleates – has a multilayered structure consisting of a large, continuous, solid lipid bilayer sheet rolled up in a spiral fashion with little or no internal aqueous space (Mozafari et al., 2006). They deliver their contents to target cells through the fusion of the outer layer of the cochleate to the cell membrane. They can be used for the encapsulation and delivery of many bioactive materials, including compounds with poor water solubility, protein and peptide drugs, and large hydrophilic molecules (Moraru et al., 2003). Liposomes can also deliver functional components such as nutraceuticals, antimicrobials, and flavors to food (Were, Bruce, Davidson, & Weiss, 2003; Ranjan et al., 2014; Sastry et al., 2013) but ultimately it is decided by the preparation methods, which may involve non-food grade solvents and detergents that might leave residues in the delivery systems and make them toxic (Mozafari et al., 2006).

3.3.2. Polymer-based nano-delivery systems

Molecules composed of regions (typically one hydrophobic and one hydrophilic monomer) with opposite affinities for an aqueous solvent can form nano-encapsulated polymers. Some of the natural biopolymers like gelatin (protein), albumin (protein) (Zwiorek, Kloeckner, Wagner, & Coester, 2005), alginate (saccharide), chitosan (saccharide), collagen (protein) and the milk protein α-lactalbumin (Graveland-Bikker & De-Kruif, 2006) are examples of such nanoencapsulated polymer delivery systems. Protein-based nano-encapsulates are particularly interesting because they are relatively easy to prepare and can form complexes with polysaccharides, lipids, or other biopolymers. A wide variety of nutrients can also be incorporated (Chen, Weiss, et al., 2006; Chen, Remondetto, & Subirade, 2006). In addition, numerous copolymers have been synthesized to date, leading to the formation of micelles, nanospheres, polymersomes, and nanocapsules (Letchford & Burt, 2007). But a fundamental understanding of polymer–polymer and polymer–nutraceutical interactions at the molecular level and their impact on functional properties of the delivery systems are required to ensure the design of ideal nutraceutical carriers for use in the food industry.

3.4. Quality control of food with sensors

The nanosensors may be able to respond to environmental changes during storage (*e.g.*, temperature, relative humidity, and oxygen exposure), degradation products or microbial contamination (Bouwmeester et al., 2009). Nanosensors integrated into food packaging systems may detect spoilage-related changes, pathogens and chemical contaminants, thus eliminating the need for inaccurate expiration dates, and thereby providing real-time status of food freshness (Liao, Chen, & Subramanian, 2005).

3.4.1. Time–temperature integrators

Time–temperature indicators or integrators (TTIs) are designed to monitor, record and translate the safety of food. This is particularly important when food is stored in conditions other than the optimal ones. For instance, if a product is supposed to be frozen, a TTI can indicate whether it had been inadequately exposed to higher temperatures and the time of exposure. The TTIs are categorized into three basic types, namely, abuse indicators, partial temperature history indicators, and full temperature history indicators (Singh, 2000). The communication is usually manifested by a color development (related to a temperature dependent migration of a dye through a porous material) or a color change (using a temperature dependent chemical reaction or physical change). Timestrip® has developed a system (iStrip) for chilled foods, based on gold nanoparticles, which is red at temperatures above freezing. Accidental freezing leads to irreversible agglomeration of the gold nanoparticles resulting in loss of the red color (Robinson & Morrison, 2010).

3.4.2. Detection of gases

Food spoilage caused by microorganisms may be detected by several types of gas sensors which have been developed to translate chemical interactions between particles on a surface into response signals. Nanosensors usually detect gases based on metal oxides. More recently, sensors based on conducting polymers which can quantify and/or identify microorganisms based on their gas emissions, are used as sensors. The change in resistance of the sensors produces a pattern corresponding to the gas under investigation (Arshak et al., 2007). Polyene and polyaromatic conducting polymers such as polyaniline, polyacetylene, and polypyrrole have been widely studied (Ahuja, Mir, Kumar, & Rajesh, 2007).

3.4.3. O_2 sensors

There has been an increasing consensus in assuring complete absence of O_2 in oxygen-free food packaging systems and to this effect there is an interest to develop non-toxic and irreversible O_2 sensors with packaging done under vacuum or nitrogen. Lee, Sheridan, & Mills, 2005 developed a UV-activated colorimetric O_2 indicator which uses TiO_2 NPs to photosensitize the reduction of Methylene Blue (MB) by triethanolamine in a polymer encapsulation medium using UV-A light. Upon UV irradiation, the sensor bleaches and remains colorless until it is exposed to oxygen, when its original blue color is restored. The rate of color change is proportional to the level of O_2 exposure (Gutiérrez-Tauste, Domènech, Casañ-Pastor, & Ayllón, 2007). Nanocrystalline SnO_2 used as a photosensitizer (Mills & Hazafy, 2009) is another sensor for detecting O_2.

3.4.4. Pathogen detection

Outbreaks of disease have resulted in export bans and the collapse of markets. To detect the presence of pathogenic organisms in food stuff, scientists at the University of Rochester Medical Center have demonstrated a new nanotechnology based method that rapidly and accurately detects *E. coli* bacteria. The technology uses a protein from the bacterium, a nano silicon chip, and a digital camera as part of its sensing system. The protein on the chip binds with any *E. coli* in the sample being tested. Once this binding has occurred, the surface of the chip is changed. The digital camera photographs this change for analysis and confirmation of detection (Garcia, Tamara, & Eric, 2010). Recently, a portable device has been developed that uses nanowires and antibodies in such a way that a single test will be able to identify the presence, type, and concentration of contamination. Pathogen specific antibodies are

Table 2
Percentage of patents and literatures in different sectors of nano-food.
Sastry et al. (2010).

Sectors	Patents (%)	Literature (%)
Food processing	15	42
Food packaging	45	22
Nutraceuticals	6	4
Safety & sensing	3	7
Nutraceuticals & packaging	9	5
Processing & packaging	17	15
Packaging and safety sensors	5	5

attached to the individual nanowires, which are then placed on the food; when exposed to fluorescent antibodies, will expose the bacteria (Garcia et al., 2010).

4. Some important intellectual property rights (IPR) in the nano-agri-food sector

Any assessment of emerging technologies like nanotechnology is challenging, as most research is at an early-stage; some of them are purely conceptual and some theoretically have been proven. Application of nanotechnology to agri-food systems is still at nascent stage to permit realistic assessments. Further work needs to be done, when it comes to practical applications. Also commercialization of nanotechnology in the agri-food sector requires a thorough assessment of toxicity before it hits the market. In such situations, analysis of patents granted in the area has often been helpful in making assessments about emerging technologies (Jaffe & Trajitenberg, 2002). While most of the patents does not result in active commercialization, the growth and accumulation of patents in a new area of technology has been considered to indicate directions for subsequent investments and related product/process innovations (Schmoch, 2006). It is observed that the number of patents filed equals (or exceeds) that of publications. The percentage of patents filed and articles published in different food sectors are given in Table 2 (Sastry et al., 2010). This trend indicates that even before development and product commercialization, early-stage research in the field of nanofood is leading to technology protection. It can be said that nanotechnology research is leading to product development by the industries almost concurrent with basic research in this area (Choi & Park, 2009).

A large number of patents have been filed in the area of nano-food research. Some of the examples include: Meso-sized capsules developed for the delivery of agricultural chemicals, targeted drug delivery (Ehr et al., 2011), carbon nanotubes to enhance seed germination and plant growth (Alexandru, Mariya, Biris, & Khodakovskaya, 2011), methods for increasing crop yields and controlling the growth of weeds using a polymer composite film (Mark & Ralf, 2011), and nanoemulsions of vitamins, flavors and colorants. In order to increase the stability of the introduced active ingredient during further processing of the product: US patent no. US20080255247 describes a hydrophobic active ingredient mixed into a matrix *via* an extruder in the form of an oil-in-water emulsion (Tao, Zuobing, & Huaixiang, 2010).

Various advancements in nanotechnology for improving and enhancing quantity and quality of food to catalyze the food processing sector, from production to conservation, processing, packaging, and even waste treatment can be patented and need further investigation before commercialization (Frederick & Randolph, 1985).

5. Nano-agro-food risk and safety concerns

As with any new technology that offers significant benefits to humankind, there are risks of adverse and unintended consequences with nanotechnology. The risk is due to the small size and large surface area of nanoparticles, which allow easy dispersion, might cross anatomical barriers and showing potential toxicity. In the agriculture sector, handling of nano fertilizers and pesticides (enhanced with nanomaterials that allow easy dispersal into the soil, water, or atmosphere) by millions of small farmers can be a leading health risk. NPs could enter the food chain *via* nutrient/pesticide delivery systems or through processed foods (Rico, Majumdar, Gardea, Videa, & Gardea-Torresdey, 2011), raising concerns of toxicity in the ecosystem. Therefore, detailed life cycle analysis, particle uptake by plants, biodistribution, entry in the food chain, *etc.* need a thorough investigation before these tools are used as products in agri-food sector. A variety of factors have to be taken into consideration before the impact of NP exposure on human health is understood (Li, Muralikrishnan, Ng, Yung, & Bay, 2010). Initiatives leading to better understanding and acceptance of the products are needed for technology development. The evolution of a participatory, dynamic and responsive nanotechnology policy and coordinated risk management strategy for the Indian agriculture and food system would be needed if the positive economic impacts of nanotechnology are to reach the agrarian society (Sastry et al., 2010, 2013).

The small size, and subsequent larger surface area of nanoparticles, endows them with some highly useful and specific properties but, it also renders them biologically more active leading to unexpected and unanticipated consequences on interaction with biological systems. Smaller size also imparts a different biokinetic behavior and ability to reach more distal regions of the body (Oberdorster, Oberdorster, & Oberdorster, 2005). The occupational exposure will also increase with the growing production and use of nanomaterials in society. Environmental contamination is yet another concern. These apprehensions have generated concerns about the potential adverse effects of engineered nanomaterials on human health and the environment. Government/Regulatory Authorities and Environmental, Health and Safety (EHS) of Nanotechnology Governments and scientific authorities all over the world are realizing the importance of nanomaterial risk assessment. A thorough understanding of the mechanisms of nanoparticles entering and leaving the cells could also lead to a better understanding of NP toxicity as well as improvement in their bio-medical applications. This will enable the formulation of regulatory rules to reduce the risks involved in the field.

The UK Government commissioned The Royal Society and The Royal Academy of Engineering in June 2003, to look into the ethical, health and safety issues related to nanotechnology. The Royal Society recommended in its report "Nanoscience and Nanotechnologies: Opportunities and Uncertainties" published in 2004, that "chemicals in the form of nanoparticles or nanotubes should be treated as new substances under the existing notification of new substances regulations and in the registration, evaluation, authorization and restriction of chemicals" to trigger additional testing (RS/RAE, 2004). Committees on the Toxicity, Carcinogenicity and Mutagenicity of Chemicals in Food, Consumer Products and the Environment have also identified the risk assessment of nanomaterials as an area of interest in their 'Joint Statement on Nanomaterials Toxicology' (COT/COM/COC, 2005). The United States Environmental Protection Agency (USEPA) while recognizing the potential benefits of nanotechnology has also stressed the need for a responsible development of nanotechnology and a proactive approach. In its document-EPA 100/B-07/001 (Nanotechnology White Paper) published in 2007, it has stated "as the use of nanomaterials in society increases, it is reasonable to assume that their presence in environmental media will increase proportionately, with consequences for human and environmental exposure" (USEPA, 2007). The European Commission's Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) has also reviewed the existing information/data and issues to be considered in conducting risk assessment on nanomaterials (SCENIHR, 2009). The European Commission's Scientific Committee on Consumer Products (SCCP) issued a document titled "Opinion On Safety of Nanomaterials in Cosmetic Products" and raised a concern about large data gaps, unsuitability of existing methodologies for nanoparticle risk assessment and inadequate information regarding nanoparticles skin absorption in both normal and abnormal (diseased) skins (SCCP, 2007). Guidance documents on safe handling of nanomaterials are also being drafted by researchers (Dhawan, Shanker, Das, & Gupta, 2011; Dhawan, Sharma, & Parmar, 2009). Non-governmental organizations like the Friends of the Earth warned against nanotechnology in cosmetic and sunscreen products, since they may result in a possible uptake of particles by human skin: if nanoparticles penetrate the skin, they can join the bloodstream and circulate around the body with uptake by cells, tissues and organs (FOE, 2006).

6. Conclusion and future perspectives

To conclude, though the era of nanotechnology is in the naive stage, it is fast evolving and has become one of the fastest growing branches of modern science. At present, every field in science is in one way or the other related to nanotechnology. Right from farming practices to marketing and trading, nanotechnology has brought about a revolution. Food and agriculture are the two major sectors that have infused confidence among scientists about the credits and credibility of nanotechnology. Synthesis and large scale application of nanoparticles in the agriculture sector led to a revolutionary change resulting in high productivity in some of the major areas. Agricultural WQM, agro-product processing, storage and distribution, quality control with nanosensors, *etc.* have brought about huge profit to farmers. Advancements in food processing, packaging, proper deliver of nutraceuticals and quality control with nanosensors have added delight to the farming community. In the near future, many of such products can be developed for efficacy. Development of an integrated nanomaterial–microbial system to be used as water purifier; food grade nanoemulsion to be used in fruit juice and other drinks; nanomaterial conjugated with activated charcoal to be used in agricultural products' processing and storage so as to enhance their antimicrobial activity; plant extracts to be conjugated with nano-food packaging for enhanced properties; nutraceutical delivery efficiency improvement using nanotechnology, *etc.* are some of the future directions in the field. Though several research groups worldwide are working on applications of nano-agro-technology, there is only a very meager understanding on the toxicological aspects of nanoparticles and the mechanism of nanotoxicology among the scientific community. Many more advancements are required to develop nano-food technology into a fully functional branch of modern science. Some of the future aspects that need special mention are: characterization and standardization of the various research parameters (which may vary from instrument to instrument and also due to differences in methodology adopted), methodical characterization and standardization of analytical instruments, development of standard protocols to identify and characterize biological and food matrices. Further, efforts can be taken by leaders in the field to develop a proper method to validate and quantify various data produced by different groups of workers worldwide. Detection and identification of nanomaterials in working samples, especially in biological samples, is at times, very challenging. Schemes should be formulated and methods developed to detect the presence of nanomaterials using proper instruments. Furthermore, a proper correlation between size and physico-biological properties like toxicology, cell–cell interaction, effect of bioactive compounds, *etc.* in presence of nanocompounds are altogether not yet explored. Unlike proteins or other biological samples that can be detected and quantified, presence of nanomaterials cannot be quantified in samples. Unless the nanomaterials is properly detected and quantified, it is futile to design further systems. There is a severe lack of scientific data among research communities for different regulatory agencies (like FDA or WHO) to assess and provide risk management guidelines. Advances in these directions will be gratifying and can indeed contribute to the emergence of nanotechnology as a fast expanding branch of science.

Additionally, more research is needed for the application of nanotechnology in aquatic and terrestrial systems as well as their interaction with organisms and the biomolecules. It is needed to enhance the knowledge and awareness of nanotechnology applications in both agriculture and farming systems *e.g.* fertilizers, enhanced nutrition, WQM, biosensors, *etc.* for farmers as well as industrial personnel and researchers. The nanoeducation should also connect schools, colleges, research centers, small scale industries and consumers to understand the potential benefits as well as risk and safety aspects of nanotechnology.

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Appendix A. Supplementary data

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