Environ Chem Lett (2017) 15:591–605
DOI 10.1007/s10311-017-0648-9

REVIEW

Applications of nanotechnology in agriculture and water quality management

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Received: 31 May 2017 / Accepted: 6 June 2017 / Published online: 14 June 2017

Abstract Due to their small size and unique physicochemical characteristics, nanomaterials have gained importance in the agri-food sector, notably in preservation and packaging. Future applications will focus on shelf life, food quality, safety, fortification and biosensors for contaminated or spoiled food, irrigating water and drinking water. Different types and shapes of nanomaterials are being used depending upon the needs and nature of the work in agriculture and water quality management. Here we review the application of nanotechnology in agriculture. The major points discussed are: (1) Nanomaterials for agriculture and water quality management. (2) Research interests such as nanoscale carriers, fabricated xylem vessels, nanolignocellulosic materials, clay nanotubes, photocatalysis, bioremediation of resistant pesticides, disinfectants, agricultural wastewater treatment, nanobarcode technology, quantum dots for staining bacteria and nanobiosensors. (3) Nanotechnological applications for agriculture, which includes nanolignodynamic metallic particles, photocatalysis, desalination, removal of heavy metals and wireless nanosensors.

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Keywords Nanotechnology · Nanomaterials · Agriculture · Water quality management · Environment · Research trends · Opportunities

Introduction

The term 'nano' is coined from the Greek word for dwarf. A nanometre (nm) is one-billionth of a metre or approximately one hundred thousandth of the width of a human hair. Nanotechnology has many applications in biotechnology and its allied field, e.g. tissue engineering, drug delivery, biomedical engineering, food science and technology among others (Danie Kingsley et al. 2013; Ranjan et al. 2014; Dasgupta et al. 2015). A wide range of applications of nanotechnology are also emerged into the 'agri-food sector' which include the nanosensors, tracking devices, targeted delivery of required components, food safety, new product developments, precision processing, smart packaging and others (McClements et al. 2009; Huang et al. 2010; Ranjan et al. 2014; Dasgupta et al. 2015). Nanotechnology can also improve the water solubility, thermal stability and bioavailability of the functional compounds of food (McClements et al. 2009; McClements and Li 2010). Figure 1 represents the major applications of nanotechnology in food processing and packaging, and the same has already been discussed in many review articles earlier.

Agricultural products influence most aspects of life, including everyday materials, such as fuels, textiles, furniture, feedstock for biobased products including food and feed. Technology advancement is needed to achieve the future global needs from agriculture. Nanoscience and nanotechnology have shown great potential in improving food safety, quality, product traceability, nutrient delivery,

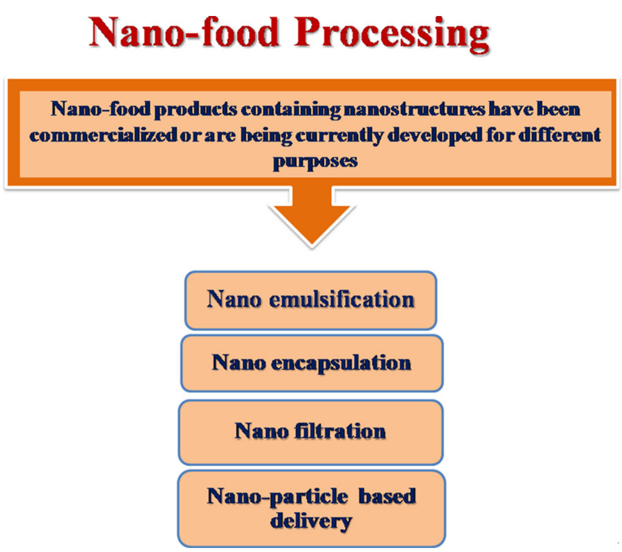

Fig. 1 Major types of nanostructures or processes which are being used to develop nanofoods to be launched in market

enhancing packaging performance, and improving agricultural and food processing. In the present review, an attempt has been made to summarize the classification and the synthesis method for the nanomaterials used in agricultural practices and water quality management. Also, the application of nanomaterials in the agriculture such as nanoscale carriers, fabricated xylem vessels, nanolignocellulosic materials, clay nanotubes, photocatalysis, bioremediation of resistant pesticides, disinfectants, agricultural wastewater treatment, nanobarcode technology, quantum dots for staining bacteria, different types of nanobiosensors along with the current research trends, future directions, opportunities and research gaps in this field has been discussed in detail. The goal of this article is to provide the perspectives of researchers working with nanotechnology to address agricultural and water quality management problems. This article is an abridged version of the chapter published by Dasgupta et al. (2016a) in the series Sustainable Agriculture Reviews.

Nanotechnology and research trends in agriculture

Nanotechnology, this vast field of the twenty-first century, is making a very significant impact on the world's economy, industry and people's lives (Gruère 2012; Dasgupta et al. 2016a). Applications of nanotechnology in materials science and biomass conversion technologies applied in agriculture are the basis of providing food, feed, fibre, fire and fuels. Through advancement in nanotechnology, a number of state-of-the-art techniques are available for the improvement in precision farming practices that will allow precise control at nanometre scale. Nanotechnology can also be an alternative source of fertilizer. In an experiment, it was observed that SiO_2NPs enhanced germination in tomato (*Lycopersicum esculentum*) seeds (Siddiqui and Al-Whaibi 2014).

Nanoscale carriers

Nanoscale carriers can be utilized for the efficient delivery of fertilizers, pesticides, herbicides, plant growth regulators, etc. The mechanisms involved in the efficient delivery, better storage and controlled release include: encapsulation and entrapment, polymers and dendrimers, surface ionic and weak bond attachments among others. These mechanisms help improve stability against degradation in the environment and ultimately reduce the mass/amount to be applied, which reduces chemical run-off and alleviates environmental problems. These carriers can be designed in such a way that they can anchor the plant roots to the surrounding soil structure and organic matter. This can only be possible through the molecular and conformational mechanisms between the delivery nanoscale structure and targeted structures and matter in soil (Johnston 2010). These advances will help in increasing the bioavailability of active ingredients, thereby reducing the amount of inputs to be used and also the waste produced. Cai et al. (2014) developed nanoclays which can be added to traditional fertilizer to improve the retention capacity of nitrogen. Thus, nitrogen loss is reduced and sufficient nutrition is provided to crops. Many nanoemulsions have also been formulated to increase the bioavailability of herbicide and pesticide (Lim et al. 2012; Jiang et al. 2013; Pant et al. 2014).

Fabricated xylem vessels

Recent advancement in nanofabrication and characterization tools has enabled the study of physico-chemical and biological interactions of plant cell bodies and various disease-causing organisms. These tools are useful in understanding the mechanisms of pathogenesis and ultimately improved the strategies for the treatment of these diseases (Cursino et al. 2009; Chen and Yada 2011). To study xylem-inhabiting bacteria, changes in bacterial populations were monitored through destructive sampling techniques at different distances from inoculation sites, but this does not provide information about colonization, film development, and subsequent movement and re-colonization at new areas because the same sample site cannot be followed temporarily. It has only been through the discovery of microfabricated xylem vessels with nanosized features that we are able to study the above mechanisms which otherwise was not possible through traditional methods (Zaini et al. 2009; Ditta 2012). A probe is used 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 (Wegner 2012). A detailed description of nanotechnology in fabricated xylem vessels has been described by Bandyopadhyay et al. (2013), and fabricated xylem system in the form of nanolitre-/picolitre-scale fluidic systems has been summarized (Hamon et al. 2013). Biomimicking of micro-/nanofabricated xylem vessels system by using microbes, for example, researchers have looked at the attachment behaviour of *Xylella fastidiosa* (De La Fuente et al. 2007) and *Escherichia coli* (Sirinutsomboon et al. 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 (Bhushan 2011; Wang et al. 2014). To control the photoluminescent emission, Carlos et al. have used ZnO and Al_2O_3 nanoparticles in *Calamus rotang* plant *in natura* xylem samples (Rambo et al. 2013).

Nanolignocellulosic materials

Recently, nanosized lignocellulosic materials have been obtained from crops and trees which had opened a new market for innovative and value-added nanosized materials and products, e.g. nanosized cellulosic crystals have been used as lightweight reinforcement in polymeric matrix (Laborie 2009). These can be applied in food and other 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 for fibre 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. 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—since we can derive nanolignocellulosic materials from lignin- and cellulose-based agricultural waste (Brinchi et al. 2013; He et al. 2014).

Clay nanotubes

Clay nanotubes (Halloysite) have been developed as carriers of pesticides for low cost, extended release and better contact with plants, and they will reduce the amount of pesticides by 70–80%, hence reducing the cost of pesticide and also the impact on water streams (Murphy 2008). The sorptive and electrical behaviour of nanocomposites (polylactide and carbon nanotubes/smectite clay nanocomposites) was studied and found that polylactide nanocomposites are endowed with increased sorption and outstandingly enhanced conductivity (up to six or even nine orders of magnitude) with respect to the pristine polymer (conductivity $= 1 \times 10^{-10}$ S/m) (Santangelo et al. 2011). This increased sorptive and increased conductivity properties of nanocomposites may have the future application as selective purification of water, and also this property can be applicable in plant–soil–water interface to increase the ion transport and sorption of nutrients. Hsu and Jehng (2009) have synthesized and characterized carbon nanotubes on clay minerals with the application of biosensor for glucose and hydrogen peroxide detection (Hsu and Jehng 2009)—which may have major applications in pre- as well as post-harvested agricultural products and their quality control. Sinha Ray (2013) has highlighted the tensile strength of clay/carbon nanotubes which may further be used in agricultural fields to provide strength to the crops and protect them from strong wind (Sinha Ray 2013).

Photocatalysis

One of the processes using nanoparticles is photocatalysis. It involves the reaction of catalyst with chemical compounds in the presence of light. The mechanism of this reaction is that when nanoparticles 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 (Ji et al. 2011). These are excellent oxidizing agents and include metal oxides like TiO_2 (Bhatkhande et al. 2002; Khataee et al. 2013), silver (Ji et al. 2011), gold (Chauke et al. 2011), ZnO (Li and Haneda 2003; Mahmood et al. 2011), SnO_2 (Ko et al. 2009), platinum (Jiang and Shangguan 2015), Ag-α-Fe_2O_3 nanocomposites (Zhang et al. 2014a) and lanthanum ferrite nanoparticles (Abazari et al. 2014), as well as sulphides like ZnS (Feigl et al. 2010) and CdS (Guo et al. 2014). As the size of particles decreases, surface atoms are increased, which results in tremendous increase in chemical reactivity and other physico-chemical properties related to some specific conditions such as photocatalysis and photoluminescence. 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), e.g. pathogens. Ankita and Vidya have remediated reactive blue 220 dye with solar light-induced photocatalytic degradation by using Ag core–TiO_2 shell (Ag@TiO_2) nanoparticles. They found higher rate of photocatalysis under solar light as compared to UV light, and also Ag@TiO_2 is a better photocatalyst than Degussa P25,

TiO_2NP and Ag-doped TiO_2 nanoparticle. It can be noted that Degussa P25 is a 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 (Khanna and Shetty 2014). Using nanotitania, Pigeot-Rémy et al. 2011 have used TiO_2 nanoparticle for photocatalysis and disinfection of water and also to decrease target bacterial load and a rectangular photoreactor has been designed and optimized . Recent research trend is shifting towards finding doped nanoparticles with better efficiency for photocatalysis (Chakma and Moholkar 2015; Khataee et al. 2015; Naraginti et al. 2015; Tahir and Amin 2015).

Nanobioremediation

Nanoparticles can be used for the bioremediation of resistant or slowly degradable compounds like pesticides. These harmful compounds tend to join the positive holes, are degraded and converted into non-toxic compounds. Otherwise, these harmful compounds enter the food chain and result in serious problems for the body; hence, nanoparticles can be used for environmental safety (Lhomme et al. 2008). The main applications of nanotechnology in bioremediation (nanobioremediation) are as uranium remediation, hydrocarbon remediation, groundwater and wastewater remediation, solid waste remediation, heavy metal remediation. Some main nanomaterials involved in nanobioremediation are as: nanoiron and its derivatives, nanosized dendrimers, carbon nanotubes, single enzyme nanoparticles, engineered nanoparticles, etc. (Ingle et al. 2014; Rizwan et al. 2014). Engineered polymeric nanoparticles have been used in bioremediation of hydrophobic contaminants (Tungittiplakorn et al. 2005) and soil remediation (Tungittiplakorn et al. 2004). Biogenic uranite nanoparticles have been used for uranium bioremediation (Bargar et al. 2008). Biologically synthesized nanomaterials from organisms *Gundelia tournefortii*, *Centaurea virgata*, *Reseda lutea*, *Scariola orientalis*, *Eleagnum angustifolia*, *Bacillus* sp. and *Noaea Mucronata* accumulated heavy metals—mainly Cu, Zn, Pb and Ni (Sinha et al. 2011; Ingle et al. 2014; Rizwan et al. 2014).

Disinfectants

The electron hole pair, especially the negative electrons resulting from the excitation of nanoparticles, can also be used as a disinfectant of bacteria, as when bacteria make contact with nanoparticles, the excited electrons are injected into their bodies, which results in the bacterial removal from the object concerned, as in fruit packaging and food engineering (Melemeni et al. 2009). Comparatively nanoparticles are better disinfectants than chemical disinfectants, e.g. sodium hypochlorite (NaClO) and phenol (C_6H_5OH) (Chamakura et al. 2011). Wei et al. have concluded that the porous Ca–Si-based nanospheres may be developed into a new intracanal disinfectant-carrier for infected canal treatment (Fan et al. 2012). Nanodisinfectant in the form of biofilm has shown improved antimicrobial activity for *salmonella* and *staphylococcus* Sp. (Arciola et al. 2012; Steenackers et al. 2012; Kumar and Ting 2013; Nithila et al. 2014).

Wastewater treatment

In modern environmental science, the removal of wastewater is an emerging issue due to its effects on living organisms (Mulligan et al. 2001; Babula et al. 2008). Many strategies have been applied for wastewater treatment including nanotechnology. Photocatalysis can be used for purification, decontamination and deodorization of air. It has been found that semiconductor-sensitized photosynthetic and photocatalytic processes can be used for the removal of organics, destruction of cancer cells, bacteria and viruses. Application of photocatalytic degradation has gained popularity in the area of wastewater treatment (Melemeni et al. 2009). The detailed mechanism of action (Fig. 2) for bactericidal/antimicrobial activity of nanomaterials has been described (Janardan et al. 2016; Nandita et al. 2016; Ranjan and Ramalingam 2016; Ranjan et al. 2016a; Walia et al. 2017). There will be differences between the mechanism of action for bactericidal activity of metal and metal oxide NPs (Dizaj et al. 2014). Understanding the differences in inactivation mechanisms helps to identify rate-limiting steps involved in the inactivation process as well as to develop more effective disinfection strategies. Detailed discussion on wastewater treatment is given in later section of this article.

Nanobarcode technology

In our daily life, identification tags have been applied in wholesale agriculture and livestock products. Due to their small size, nanoparticles have been applied in many fields ranging from advanced biotechnology to agricultural encoding. Nanobarcodes (>1 million) have been applied in multiplexed bioassays and general encoding because of their possibility of formation of a large number of combinations that make them attractive for this purpose. The UV lamp and optical microscope are used for the identification of micrometre-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 encodable, machine-readable, durable, sub-micronsized taggant particles. For the manufacture of these nanobarcode particles,

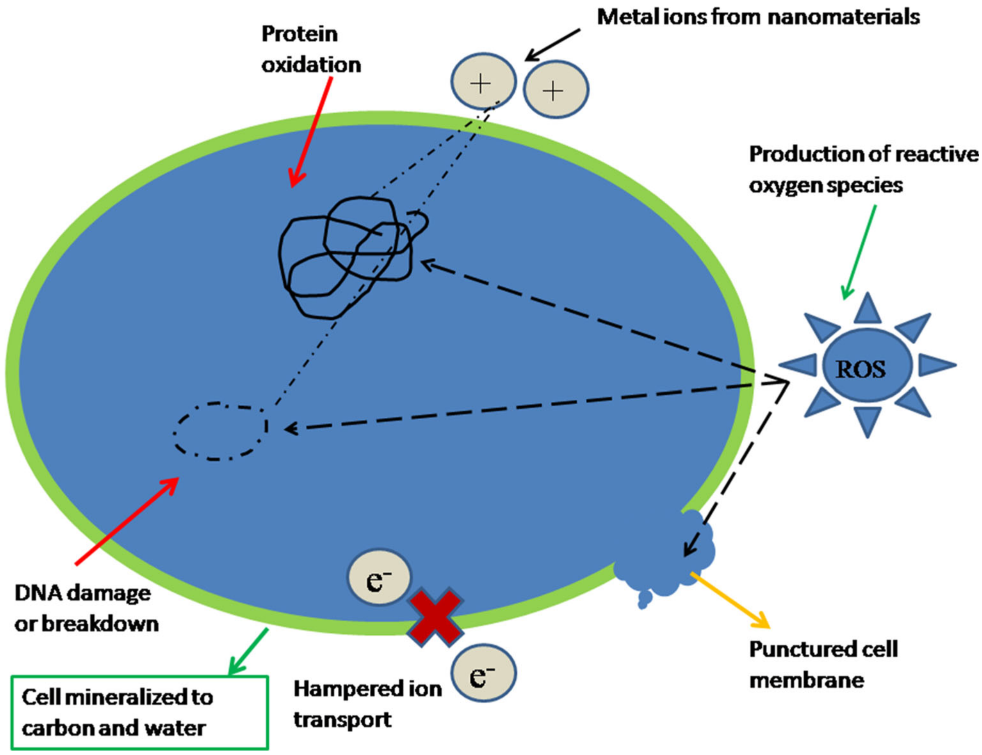

Fig. 2 Mechanism of bacteria cell damage by induction of reactive oxygen species (*Courtesy* Dasgupta and Ramalingam 2016)

the process is semiautomated and highly scalable, involving the electroplating of inert metals (gold, silver, etc.) into templates defining particle diameter, and then, the resulting striped nanorods from the templates are released. These nanobarcodes have the biological as well as non-biological applications (Mathew et al. 2009). Cost-effective nanobarcode technology development is a major challenge for the researchers—this can be concluded based on the fact that total of 18 documents found on Scopus indexed article database (SIAD). Out of 18 articles, notes (one in number), conference paper (six in number) review article (two in number) and only nine research articles were available in last 10 years by the keyword of 'nanobarcode'(SIAD 2014). Similarly, only 32 articles are present in SciFinder® database with the same keyword. After refining it with year-wise, none of the articles were found for 2014; only one article in duplicate was found by Han et al. 2013 which has been discussed earlier; similarly, only three articles have been found for the year 2012, but none of them have described the application of nanobarcode in agricultural field (SciFinder 2014). This shows that development of nanobarcode technology for agricultural application is one of the thrust areas.

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, diseases and others 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).

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

Quantum dots for staining bacteria: There are numerous bacteria which are responsible for many diseases in humans like tetanus, typhoid fever, diphtheria, syphilis, cholera, food-borne illness, leprosy and tuberculosis caused by different species. As a remedial process, we need to detect bacteria, and for this, dye staining method is used. To stain bacteria, the most commonly used biolabels are organic dyes, but these are expensive and their fluorescence degrades with time. So the need of the hour is to find durable and economical alternatives. Fluorescent labelling by quantum dots with biorecognition molecules has been discovered through the recent developments in the field of luminescent nanocrystals. Quantum dots are better than conventional organic fluorophores (dyes) due to their more efficient luminescence compared to the organic dyes, narrow emission spectra, excellent photostability, symmetry and tunability according to the particle sizes and material composition. By a single excitation light source, they can be excited to all colours of the quantum dots due to their broad absorption spectra (Warad et al. 2004). Biolabelled bacillus bacteria 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, quantum dots were used as a fluorescence marker coupled with immune magnetic separation (Su and 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. Quantum dots were labelled with the immune complexes via biotin streptavidin conjugation after magnetic separation.

Biosensors and electronic nose

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 odour 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 for poisoning. Therefore, it is more sensible to use an instrument like rapid detection biosensors for the detection of these odours (Compagnone et al. 1995). The future application of nanobiosensors is recently developed by Zhang et al. (2014b, c). Nanobiosensors are hot area of interest in the fields 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 Rocha-Santos (2014). ZigBee™ is a wireless mesh networking standard with low cost and 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 et al. 2010). Through this wireless sensor technology with nanoscale sensitivity, we can control plant viruses and level of soil nutrients, as the plant surfaces can be changed at nanoscale with specific proteins. This technology is important in realizing the vision of smart fields in particular. Wireless network sensor technology can also be used for monitoring the optimal conditions for mobile plants biotechnology.

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 (Türkoğlu et al. 2013; Labroo and Cui 2014).

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 on the basis of immobilization surface are classified into four groups (1) controlled-pore glass beads with optical transducer element, (2) polyurethane foam with photothermal transducer element, (3) ion-selective membrane with either potentiometric or amperometric transducer element and (4) screen-printed electrode with amperometric transducer element (Patel 2002). Considering microbial contamination, a device electrogenerated chemiluminescence immunosensor has been found by using Fe3O4@Au to detect *Bacillus thuringiensis* (Li et al. 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 and Stanker 2013). While considering aquaculture—to measure volatile amines levels in fishan—optical fibre-based microanalyser was designed—this has future aspect to develop such nanobiosensor instead of micro (Silva et al. 2010).

Electronic nose is a device based on the operation of the human nose and is used to identify different types of odours; 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 odour in the same way as might be perceived by the human nose. It mainly consists of gas sensors which are composed of nanoparticles, e.g. ZnO nanowires (Hossain et al. 2005; Sugunan et al. 2005). ZnO nanorods are used to develop electronic nose which can detect impurities from vapour mixture (Ko et al. 2013). Their resistance changes with the passage of a certain gas and 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 odour being detected. There is also an improved surface area which helps in better absorption of the gas.

Gold nanoparticles

Gold nanoparticles, commercially used as rapid testing arrays for pregnancy tests and biomolecule detectors, are based on the fact that the colour of these colloids depends on the particle size, shape, refractive index of the surrounding media and separation between the nanoparticles. A quantifiable shift in the surface plasmon response (SPR) absorption peak results due to a small change in any of these parameters. We can make these nanoparticles attach to specific molecules by carefully choosing the capping agent for stabilizing gold nanoparticles. These specific molecules get adsorbed on the surface of these nanoparticles and change the effective refractive index of the immediate surroundings of the nanoparticles (Nath and Chilkoti 2004; Li et al. 2010). A few nanoparticles will be adsorbed if the detecting molecules (biomacromolecules) are larger than the gold nanoparticles and result in the formation of lumps after agglomeration. Ultimately, colour of gold nanoparticles is changed due to shift in SPR that result from the reduction in particle spacing. These properties provide a great opportunity to use gold nanoparticles for biosensor development. In the field of pharmaceutical science and other biomedical fields, many gold nanoparticles-based biosensors have been already developed for detection of enzyme activity—the same should be researched in the field of food, agriculture and water quality management (Hutter and Maysinger 2013).

Nanotechnology and research trends in water quality management

Currently, provision of clean and abundant fresh water is one of the most important challenges faced by the world for human use and industrial applications such as agriculture (Vörösmarty et al. 2010; Ditta 2012). According to a survey, more than one billion people in the world are deprived of clean water and the situation is getting worse. In the near future, it has been estimated that 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. Meanwhile, non-contaminated water is also not available for proper agricultural practices (Cross et al. 2014). 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, novel, sustainable and cost-effective technologies will be required for the treatment of this large amount of waste water produced. During the treatment of wastewater, critical issues like water quality and quantity, treatment and reuse, safety due to chemical and biological hazards, monitoring and sensors should be considered (Thorburn et al. 2013; Schoumans et al. 2014). Research and development in nanotechnology have enabled us to find novel and economically feasible solutions for remediation and purification of this wastewater. Accessible water resources are mostly contaminated with waterborne pathogenic microorganisms like cryptosporidium, coliform bacteria and virus, various salts and metals (Cu, Pb, As, etc.), run-off agricultural chemicals, tens of thousands of compounds considered as pharmaceuticals and personal care products (PPCP), and endocrine-disrupting compounds (EDC) and radioactive contaminants, either naturally occurring or as the result of oil and gas production as well as mining activities due to natural leaching and anthropogenic activities (Jasra et al. 1999). Nanoscale zero-valent iron can be used for the treatment of distillery wastewater (Homhoul et al. 2011). For improving water quality, nanotechnology has provided novel solutions.

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 are lacking these systems due to the requirement of large infrastructure which make them costly. The need of the hour is to search and develop alternative cost-effective technologies. Nanotechnology-based oligodynamic metallic particles have the ability to serve this function. Among these nanomaterials, silver is the most promising one as it is both bactericidal and viricidal due to the production of reactive oxygen species that cleaves DNA and can be utilized for a wide range of applications. Other properties include low toxicity, ease of use, its charge capacity, high surface-to-volume ratios, crystallographic structure and adaptability to various substrates (Nangmenyi et al. 2009; Chen and Yada 2011; Faunce et al. 2014). Recently, researches have been done to vary the size of silver and gold nanoparticles with simple approaches, i.e. changing the concentration of reactants. The improved activity of antimicrobial and anticancerous activity was observed for them (Sireesh et al. 2015, 2017; Dasgupta et al. 2016c; Jain et al. 2016; Shukla et al. 2017; Siripireddy et al. 2017; Tammina et al. 2017). It also can be noted that recently trends are changing towards in silico and computational as well as in vitro approaches towards toxicity evaluation of inorganic nanoparticles at biomolecular level (Ranjan et al. 2015, 2016b; Dasgupta et al. 2016b; Jain et al. 2016).

Photocatalysis

Visible light photocatalysis of transition metal oxides, another nanoscale technological development, produces nanoparticles, nanoporous fibres and nanoporous foams that can be used for microbial disinfection (Qi et al. 2009) and for the removal of organic contaminants like PPCPs and EDCs. Moreover, tubular nanostructures, embedded into microbial cell wall, can disrupt its cell structure resulting in the leakage of intracellular compounds and ultimately cell death. A detailed research trend in the field of photocatalysis has been discussed above in detail. As discussed above, the recent research trends for photocatalysis using nanomaterials have been shifted from single nanoparticles to hybrid nanocomposite, 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 nanopagodas array with enhanced photocatalytic activity (Chiu et al. 2015); PbS quantum dots in ZnO@PbS/graphene oxide has been synthesized for enhanced photocatalytic activity (Shi et al. 2015); zirconium and silver co-doped TiO_2 nanoparticles for degradation of methyl orange and methylene blue (Naraginti et al. 2015).

Desalination

Due to 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: (1) protein–polymer biomimetic membranes, (2) aligned carbon nanotube membranes and (3) thin film nanocomposite membranes (Hoek and Ghosh 2009; Nikonenko et al. 2014). 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, defouling and self-cleaning. In another approach, zeolite nanomembrane can be used for seawater desalination (Liu and 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 (Ranjan et al. 2016c, d; Shivendu et al. 2016). Desalination using nanotechnology with the aspects of carbon nanotubes (Das et al. 2014), reverse osmosis (Lee et al. 2011), forward osmosis for seawater and wastewater (Valladares Linares et al. 2014) has been reviewed earlier. Recently, many devices with improved efficiency and performance have been developed—self-sustained webs of polyvinylidene fluoride electrospun nanofibres (Essalhi and Khayet 2014); PVA/PVDF hollow fibre composite membrane modified with TiO_2 nanoparticles (Li et al. 2014); novel integrated system coupled with nanofluid-based solar collector (Kabeel and El-Said 2013, 2014); zinc oxide micro-/nanostructures grafted on activated carbon cloth electrodes (Myint et al. 2014); tubular MFI zeolite membranes (Drobek et al. 2012); titanium oxide nanotubes/polyethersulfone blend membrane (Abdallah et al. 2014); graphene-wrapped MnO_2 nanostructures (El-Deen et al. 2014b); thin film nanocomposite membranes (Subramani et al. 2014); graphene/SnO_2 nanocomposite (El-Deen et al. 2014a); carbon nanotubes (Goh et al. 2013).

Removal of heavy metals

Ligand-based nanocoating can be utilized for effective removal of heavy metals as these 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. According to another strategy, for the removal of heavy metals is the use of dendrimer-enhanced filtration and it can bind cations and anions according to acidity. Nowadays, nanomaterials have been widely used to remove heavy metals from water/wastewater due to their large surface area and high reactivity. Metal oxide nanoparticles, including nanosized ferric oxides, manganese oxides, aluminium 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 nanoparticles, to evaluate their removal of heavy metals under varying experimental conditions, to reveal the underlying mechanism responsible for metal removal based on modern analytical techniques (XAS, ATR-FTIR, NMR, etc.) or mathematical models and to develop metal oxide-based nanomaterials of better applicability for practical use, i.e. granular oxides or composite materials (Hua et al. 2012; Kumar and Chawla 2014). 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 behaviour of nanomaterials, but also influence the removal and transportation of heavy metals by nanomaterials. Thus, the interactions and the underlying mechanisms involved warrant-specific investigations. Tang et al. 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. Mainly they have discussed the mechanisms involved in the interactions and evaluated the potential environmental implications of humic acid and fulvic acid to nanomaterials and heavy metals (Tang et al. 2014).

Wireless nanosensors

Crop growth and field conditions like moisture level, soil fertility, temperature, crop nutrient status, insects, plant diseases and weeds 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 and Chen 2013). Scientists and engineers are working to develop the strategies which can increase the water use efficiency in agricultural productions, e.g. drip irrigation. This has moved precision agriculture to a much higher level of control in water usage, ultimately towards the conservation of water. More precise water delivery systems are likely to be developed in the near future. These factors critical for their development include 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 nanosensor systems (Cross et al. 2014). Sensing and detection of various contaminants in water at nanoscale under laboratory and field conditions has remained a hot issue over the last decade. In the near future, state-of-the-art nanotechnology-based techniques will help in developing many new technologies that will have better detection and sensing ability (Chen and Yada 2011). Similar to nanobarcode development, wireless nanosensor development for WQM is one of the vital fields of the research. Sensor networks are a key technological and economic driver for global industries in the near future, with applications in health care, environmental monitoring, infrastructure monitoring, national security and more. Developing technologies for self-powered nanosensors is vitally important. Wang (2012) has given a brief summary about recent progress in the area, describing nanogenerators that are capable of providing sustainable self-sufficient micro-/nanopower sources for future sensor networks. Negligible research work has been done in the field of wireless nanosensor development (SciFinder 2014; SIAD 2014) out of which mostly are conceptual notes and/or book chapters and reviews. Mannoor et al. (2012) have done an outstanding work after developing wireless graphene-based nanosensor for detection of bacteria. In particular, they have demonstrated integration onto a tooth for remote monitoring of respiration and bacteria detection in saliva. Since they have developed a wireless nanosensor to detect bacterial load in saliva which is an aqueous phase—by keeping this concept in mind one can think about developing such device for bacterial load detection.

It can be noted that other than food and agriculture, nanotechnology has grown interest in many fields. Figure 3 depicts the trends in patents in different allied fields of nanotechnology in last few years (Pérez-Esteve et al. 2011, 2013). The beneficial properties—increased surface area, apparent solubility, good retention time, direct uptake of nanomaterials and enhanced nutritional quality—open the ample scope for the nanotechnology with different applications and have the best future to cover the market which are summarized in Fig. 4. On the contrary, one should not ignore the toxicological aspect of nanomaterials on humans, animals and its impact on ecosystem, and the same has been discussed in other chapters of this book (Fig. 5).

Conclusion

Nanotechnology has not only improved the quality of modern agricultural practices by making them technical, susceptible, safer and improved quality in agricultural products nutritious, but has also helped a lot in generating new agricultural products, better packaging and storage techniques and improved the quality of the its allied field such as water quality management. Conversion of materials to its nano form helps in enhancement of their physiochemical properties and applications, e.g. silver nanoparticles shows antibacterial property, and they are being incorporated into bandages for their beneficiary effect in ailing wound; however, the bulk particles are less effective. Titanium dioxide used as an intense white pigment is opaque in nature. However, nanoparticles of titanium dioxide are transparent, and due to its physical nature, they are being used in transparent sunscreens, food packaging or plastic food containers.

Application of nanotechnology has enhanced the delivery of fertilizers, pesticides, herbicides and plant growth regulators with the help of nanoscale carriers; also its application in agricultural sector is such as fabricated xylem vessel, clay nanotubes, photocatalysis, wastewater treatment, nanobarcode technique, different types of biosensors and quantum dots for bacterial staining. In addition, nanomaterials are further researched to keep the product fresher with increased shelf life. Nanoscience and

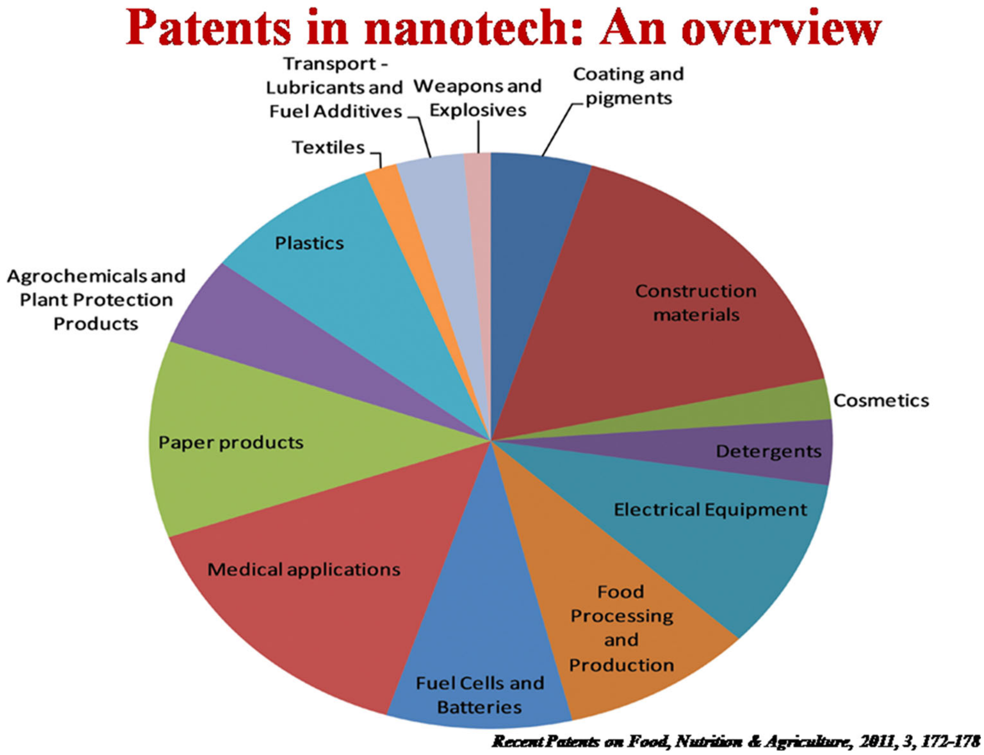

Fig. 3 Patents in nanotechnology sectors during the previous decade. It represents the sharp increase in use of nanotechnology in different sectors including agriculture and foods. (*Courtesy:* Edgar et al. 2011)

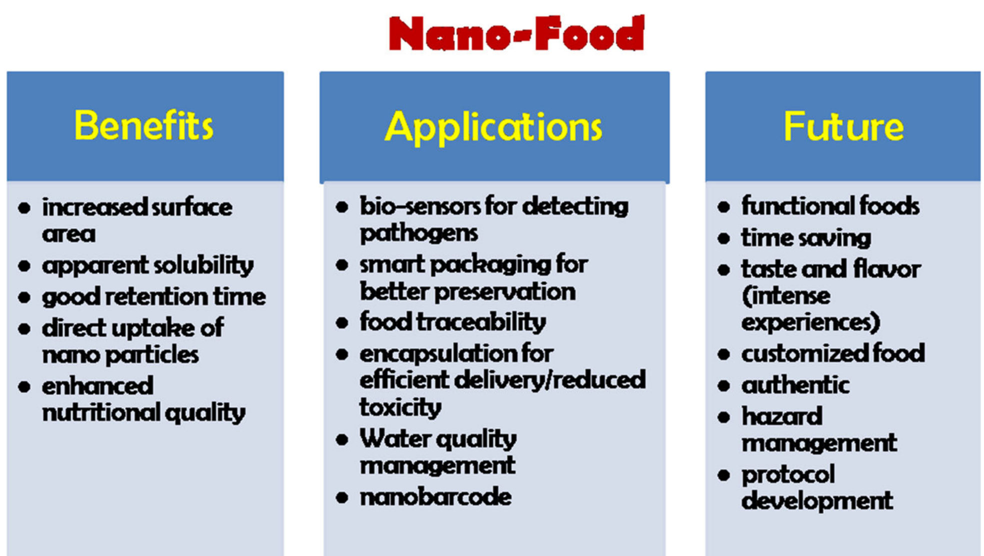

Fig. 4 Beneficial properties—increased surface area, apparent solubility, good retention time, direct uptake of nanomaterials and enhanced nutritional quality—open the ample scope for the nanotechnology with different applications and have best future to cover the market

nanotechnologies have vast applications in water quality management as heavy metal removal, nanobioremediation through nanolignodynamic metals, desalination, disinfecting process and the sensors to check the quality. Nevertheless, many of their applications are currently at a beginning stage and most of them require a high quality of research and development for their safe application. The safety of nanoparticles in agri-food industry also offers challenge to government and industry both. The food processing industry must ensure the consumer confidence and acceptance of nanofoods safety. When it comes to the application of nanotechnology in industrial scale, it is important to evaluate the release of nanoparticles into the environment and to estimate the subsequent levels of exposure to these materials. As the nanoparticles can easily penetrate into the human organ and organelles, exposure time, exposure concentrations, sites of penetration, immune response and accumulation and retention of nanoparticles

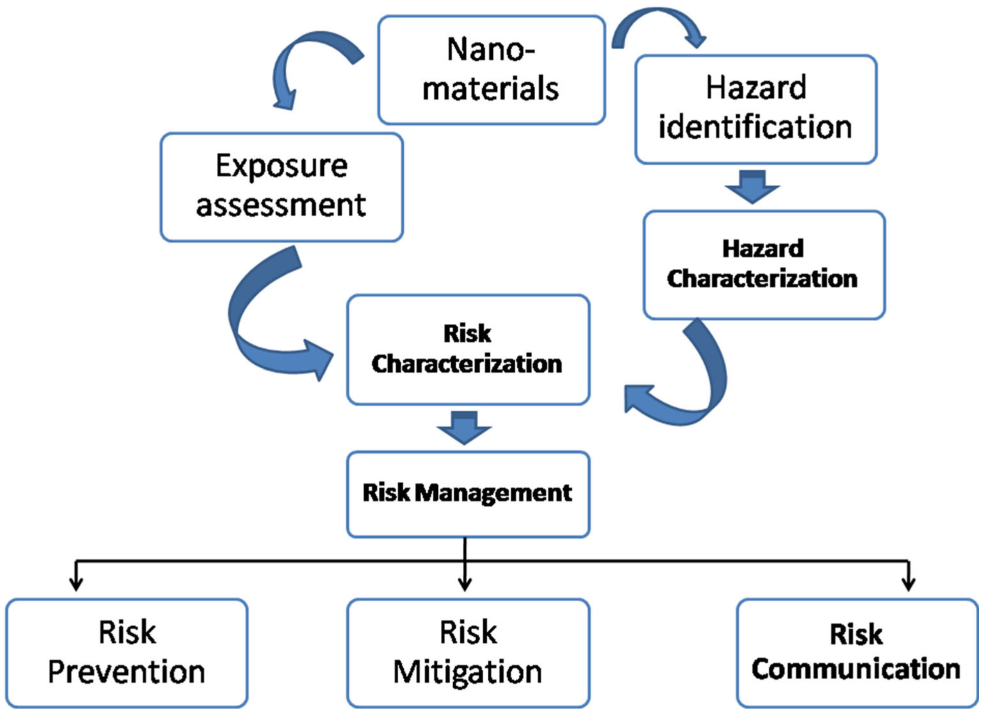

Fig. 5 Toxicological aspect of nanomaterials on humans, animals, environment and whole ecosystem. Diagrammatic representation of nanotoxicological analysis

in body and their subsequent effects should be assessed carefully.

Even though the research regarding the application of nanotechnology is growing every day, still insufficient scientific examination of naturally occurring nanosystems is available. The compulsory testing of nanomodified agricultural products and/or treated water should be performed before they allowed to be introduced into the market. Standardized test procedures are required to study the impact of nanoparticles on living cells for evaluation of the risk assessment on human exposure to nanoparticles. Toxicology of nanoparticles is poorly understood because of the lack of validated test methods and the inconsistency in the reported data. The inconsistency in the published data is due to the improper characterization of nanoparticles and the interferences induced by the nanoparticles in the available test system. Hence, the regulatory bodies and the policy makers should provide the guidance document for the validated protocols, safe uses and the disposal of the nanoparticles. The understanding of the safe application of nanoscience and nanotechnology in agri-food and water quality management will help in the sustainable growth of 'nanoagri-technology'.

Acknowledgements Authors are acknowledging Department of Biotechnology (DBT, India) for the funding with grant number—BT/PR10414/PFN/20/961/2014. SR is acknowledging Veer Kunwar Singh Memorial Trust, Chapra, Bihar, India, for partial support—VKSMT/SN/NFNA/0011.

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