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Nanotechnologies associated to floral resources in agri-food sector

Nanotecnologías asociadas a recursos florales en el sector agroalimentario

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Abstract

Nanotechnology advent in agri-food sector is set to prompt next revolution in agricultural engineering. However, there is a perpetually rising need for development of new nanotechnologies that could synchronically work with various agrochemicals such as fertilizers, pesticides, herbicides, and growth promoters to potentially increase farmlands efficiency, preserve agro-ecosystems, and diminish the negative health risks imposed by conventional practices. In nanotechnology, smart delivery systems that utilize either nanoscale carriers such as clay nanotubes and carbon nanotubes or nanoparticles such as mesoporous silica nanoparticles and silver nanoparticles, could enable not only the accurate and targeted delivery of functional ingredients but also their impartial dissemination over farmlands. Nanotechnology has found applications for bioremediation of irrigation water and agricultural runoff, crop breeding, agronomic traits via genetic manipulation of genomes at molecular level, and detection of minute quantities of contaminants and stressors as well as early detection of plant diseases and continuous monitoring of plant environment through employment of nano-biosensors. Scientists are diligently working to explore new substitutes for conventional technologies. Advancements in nanotechnology could help them to explore new frontiers and find novel applications in agri-food sector.

Keywords: Agrochemicals; bioremediation; crop breeding; micro-fabricated xylem vessels; smart delivery systems; smart nano-dust.

Resumen

El advenimiento de la nanotecnología en el sector agrícola está programado para impulsar la próxima revolución en la ingeniería agrícola. Sin embargo, existe una creciente necesidad de desarrollo de nuevas nanotecnologías que puedan trabajar sincrónicamente con diversos agroquímicos como fertilizantes, pesticidas, herbicidas y promotores de crecimiento para aumentar potencialmente la eficiencia de las tierras de cultivo, preservar los agroecosistemas y disminuir lo negativo Riesgos para la salud impuestas por las prácticas convencionales. En nanotecnología, los sistemas inteligentes de entrega que utilizan portadores a nanoescala como nanotubos de arcilla y nanotubos de carbono o nanopartículas como nanopartículas de sílice mesoporosas y nanopartículas de plata, podrían permitir no sólo la entrega precisa y específica de ingredientes funcionales sino también su difusión imparcial sobre las tierras de cultivo. La nanotecnología ha encontrado aplicaciones para la biorremediación del agua de riego y la escorrentía agrícola, la mejora de los rasgos de los cultivos mediante la manipulación genética de los genomas a nivel molecular y la detección de cantidades diminutas de contaminantes y factores de estrés, El seguimiento continuo del medio ambiente vegetal mediante el empleo de nanobiosensores. Los científicos están trabajando diligentemente para explorar nuevos sustitutos de las tecnologías convencionales. Los avances en nanotecnología podrían ayudarles a explorar nuevas fronteras y encontrar nuevas aplicaciones en el sector agrícola.

Palabras clave: Agroquímicos; biorremediación; mejora genética de cultivos; nano-polvo inteligente; sistemas inteligentes de entrega; vasos xilemáticos micro fabricados.

Introduction

The majority of developing countries rely on their agri-food sector to generate income and maintain livelihood of their inhabitants (Jahanban & Mohammadreza, 2014). However, countries throughout the world are facing challenges to meet food security since demand on agricultural products is arising. Diminishing arable land and decline in soil organic matter as well as stagnation in crop yields are amongst these challenges. Thus, to attain food security, 4% growth rate should be reached (Manimaran, 2015; Nichols, 2007). Nowadays, global agri-food sector has plateaued out (Agrawal & Rathore, 2014). Yet, with a global population growing at a rate of 1%, by year 2050, 70 % more food should be produced (Samantarai & Achakzai, 2014; Nichols, 2007). Therefore, to maximize crop yields from their fields and to cope with nutrient deficiencies, farmers resort to excessive fertilizers utilization and agro-chemical products (Manimaran, 2015; Agrawal & Rathore, 2014; NRC, 2008).

Given these concerns, to surmount the challenges faced in agri-food sector, new frontiers are ought to be explored (Manimaran, 2015). To increase farmlands productivity and mitigate negative impacts of conventional practices on environment, a plethora of technologies which could conserve both soil and water are being investigated by scientists (Ditta, 2012). Likewise, technologies in emerging frontier of nanotechnology has potential to revolutionize the agri-food sector (Biswal, Nayak, Parida & Nayak, 2012).

Nanotechnology can be defined as the engineering of functional systems through manipulation and molecules and atoms control in the nanoscale to create nanoparticles, nanomaterials, or nanoequipment which exhibit useful and distinct chemical and physical properties (Power, Brown, Krishna, Wasdo, Moudgil & Roberts, 2006; Moskvins, Spakovica, Moskvins, Shakhtarina & Beldavs, 2012; Alam, Ismat, Sayeed, Khan, Akhtar, Farooqui & Siddiqui, 2016; Narayanan, Sharma & Moudgil, 2013). The term nano, which is referred to as a billionth of a meter implies that structures manufacturing with a circumference ranging 1 and 100 nm (nano-meters) is subsumed under nanotechnology umbrella (Nowack & Speiser, 2008; Moskvins *et al.*, 2012; Ravichandran, 2010).

Furthermore, precise-farming strategies has been long envisioned by scientists as apotheosis of modern nanotechnology in agri-food sector. Advancements in nanotechnology can satisfy a rising demand on food through remodeling production methods (Ali, Rehman, Iqbal, Din, Rao, Latif, Samiullah, Azam & Husnain, 2014). Utilization of nanotechnology and nanoscale science products encompasses a wide spectrum of applications such as rapid detection of nutrients and crop diseases, treatment of diseases and fighting viruses, and accurate delivery of nutrients and pesticides, and an improvement in nutrient plant uptake (Biswal, Nayak, Parida & Nayak, 2012; Argawal *et al.*, 2014; Ali *et al.*, 2014; Manimaran, 2015).

Additionally, research in nanotechnology is giving rise to new innovative methods for plant genetic modification, fine-tuning of micro-irrigation systems, and altering kinetic profiles of drug release systems (Jahanban & Moahmmadreza, 2014; Biswal, Nayak, Parida & Nayak, 2012). Similarly, employment of nanotechnology in agri-food does not only hold the key for inputs reduction and decreasing in costs, but also enhancing nutritional plant content and extending their shelf life (Ali *et al.*, 2014).

In following sections, a handful of possible nanotechnology applications in agri-food sector will be discussed. Although the use of nanotechnology has been vastly researched, its applications remained theoretical (Sertova, 2015). A first direct effort to address practical application of nanotechnology in agri-food sector has been proposed in September 2010 by the United States Department of Agriculture in their roadmap (Samantarai & Achakzai, 2014).

Smart delivery systems

Nanoscale equipment, materials, and particles which possess unique and novel properties could transform conventional agricultural systems making them smart (Prasad, Kumar & Prasad, 2014; Alam *et al.*, 2016). Chen, Weiss & Shahidi (2006); Su, Wu, Liu, Qu, Liu, Chen, Huang & Hong (2007), portrayed the advancements in nanotechnology for development of targeted and smart delivery systems as multifunctional nanoscale nutraceutical delivery systems that do not only have the ability to detect and recognize appropriate location, but also analyze local and global needs as well as decide whether or how much payload should be released (Figure 1). Consequently, smart delivery systems would monitor the response of nanoscale nutraceutical delivery systems for feedback (Scrinis & Lyons, 2007; Ravichandran, 2010).

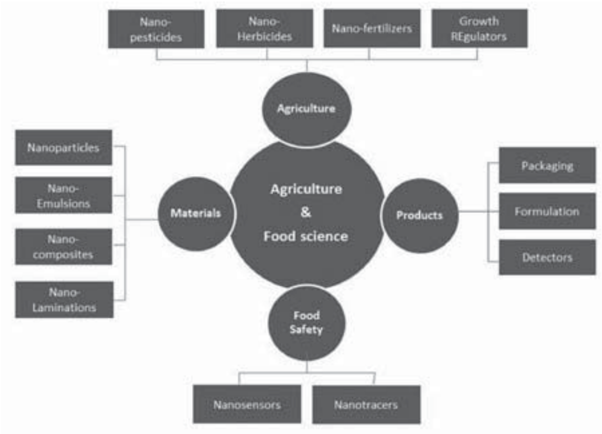

Figure 1. A pictorial demonstration of applications of nanotechnology in agri-food sector

Source: Ali *et al*. (2014).

Fabrication of smart delivery systems by using nanotechnology would help farmers usher into a new era of yield improvement, early diseases detection, infections, nutrient deficiencies, and their subsequent treatment via timely release of drugs and micronutrients (Prasad, Kumar & Prasad, 2014; Dhewa, 2015; Sertova, 2015; Alam et al., 2016; NRC, 2008).

Nanoscale devices could not only be used to identify plant health issues and treat them, but they could also warn farmers before disease signs become visible (Prasad, Kumar & Prasad, 2014; Alam *et al*., 2016). In addition, employment of nanostructured catalysts can increase pesticides and herbicides efficiency, which have allowed the use of lower doses (Sertova, 2015).

Interest in the use of smart delivery systems increased after banishment of several agrochemicals such as DDT, due to their high toxicity affecting animals and humans health, environment, albeit their use effectively improved yields (Prasad, Kumar & Prasad, 2014; Alam et al., 2016). Nichols (2007), noted that nanotechnology encompasses a wide range of applications in the smart delivery of agrochemicals and food components encapsulated or carried by nanoscale materials or particles.

Nanocapsules, nanoscale carriers, and nanoparticles

In conventional agricultural practices, several factors such as leaching, hydrolysis, photolysis, and bacterial degradation of the applied agrochemicals lead to inefficient distribution of fertilizers, pesticides, herbicides, and plant growth regulators. Nonetheless, the utilization of entrapped or encapsulated agrochemicals in nanoscale carriers, nanocapsules, or nanoparticles (Figure 2), can promote the precise and controlled delivery of agrochemicals and their subsequent balanced dispersion in plants and over farmland (Sabir, Arshad & Chaudhari, 2014; Alam *et al.*, 2016; Manjunatha, Biradar & Aladakatti, 2016).

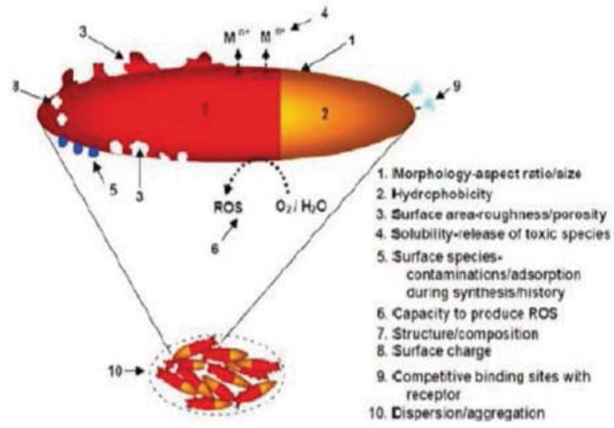

Figure 2. The properties of nanoparticles

Source: Manjunatha, Biradar & Aladakatti (2016).

Nanoscale carriers

Nanoscale carriers are smart nanoscale devices (Ali *et al.,* 2014). They comprise an environmentally-friendly emerging nanotechnology in which nanoscale carriers exhibit the ability to persist in environment for long durations. Nevertheless, their negative footprint on environment is alleviated due to substantial reduction in the applied amount of carried agrochemicals as well as decreasing in the amount of chemical runoff. Moreover, the apposite design, fabrication, and use of nanoscale carriers requires profound knowledge of molecular and conformational mechanisms that occur between the nanoscale carrier and targeted structure in soil (Ditta, 2012).

NAAS (2013), showed that nanoscale carriers such as nanotubes in polymers and dendrimers can be used to efficiently target and deliver pesticides, herbicides, fertilizers, or plant growth regulators in plants. Also, nanoscale carriers can anchor soil structure and soil organic matter to plant roots (Ditta, 2012). This process can slow down the uptake rate of active ingredients by plant roots, improve compounds stability, reduce their applied amount, reduce wastes produced, and reduce costs (Ditta, 2012; Dhewa, 2015.

Clay nanotubes

Clay nanotubes have proved to be efficient carriers of pesticides. Moreover, in rainfed rabi crops, several fungal nematode disease complexes that occur in pulses could be fought by loading and coating *Trichoderma* spp. or *Pseudomonas* spp. with nanoclay polymer nanocomposites (NCPCs) (Sen, Prakash & Nirmal, 2015). Adzmi, Meon, Musa & Yesuf (2012), noted that bioagents coated with nanoclay could retain their activity for longer periods of time and could serve other nutritional supplementation purposes too. Murphy (2008), reported that clay nanotubes can extend the release of pesticides and reduce the amount of pesticides by 70 to 80%, subsequently decreasing the cost of pesticide and diminishing its impact on water streams.

Carbon nanotubes

Carbon nanotubes are composed of carbon molecules that are held in position with strong van der Waals force. The versatility and flexibility of carbon nanotubes promoted its application in particle packaging, filtration, energy storing devices and environment monitoring devices (Scrinis & Lyons, 2007). Study of biochemical processes and manipulation of living cells at molecular level have been facilitated with the use of Carbon nanotubes (Srilatha, 2011).

In agri-food sector, crop growth rates, intake of water, and uptake of essential nutrients have been improved with the use of multi-walled carbon nanotubes (Scrinis & Lyons, 2007). Studies revealed Carbon nanotubes could be utilized as vehicles loaded with desired molecules to ease their delivery into crops during germination, which could protect the seeds from diseases. Since one of the functions of Carbon nanotubes is plant growth promotion, which implies that they do not have any adverse toxic of inhibiting effects on plant (Srilatha, 2011). Treatment of crops such as maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), peanut (*Arachis hypogaea* L.), and garlic (*Allium sativum* L.) with multi-walled Carbon nanotubes at concentration of 50 $\mu g.ml^{-1}$ increased root and shoot lenght, improved seed germination time, and enhanced their growth. Carbon nanotubes could also improve water retention in plants (Rameshaiah, Pallavi & Shabnam, 2015). Aternatively, Zimdahl (1999), mentioned that characterization of underground plant parts is imperative for the development of a receptor-based herbicide molecules such as carbon nanotubes which exhibit herbicidal effects capable of killing viable and dormant underground propagules of weed seeds.

Nanoparticles

Weiss *et al.* (2006), revealed that the application of nanoscale particles might increase functionality or bioavailability of nutrients, abating concentrations needed in agricultural and food products. Nanoparticles have shown promising results for diseases control and infections. For instance, Jayaseelan, Rahuman, Rajakumar, Vishnu, Santhosh, Marimuthu, Bagavan, Kamaraj, Zahir & Elango (2011), showed that maximum mortality rates against the head louse *Pediculus humanus* and fourth instar larvae of *Anopheles subpictus* and *Culex-quinque fasciatus* were achieved with silver nanoparticles using an aqueous leaf extract of Tinospora. Moreover, Patil (2009), revealed the use of nanotubes filled with aluminosilicate, which can be used for insect pest control. Evidently, nanotubes ingredient would penetrate insect body and ultimately alter particular physiological functions. Equally, encouraging results were recorded from the use of nanotubes filled with garlic-essential oil (Yang, Li, Zhu & Lei, 2009).

Zinc oxide nanoparticles

Crop yields and growth could be boosted through utilization of Zinc oxide nanoparticles. Treatment of peanut seeds with Zinc oxide particles at concentrations of 1000 ppm, promoted seeds germination, improved seedlings vigor, and increased plant stem and roots. In addition, nanofertilizers such as colloidal solution of Zinc oxide nanoparticles play an important role in agri-food sector (Sabir, Arshad & Chaudhari, 2014).

Silver nanoparticles

Silver nanoparticles are not only known for their board spectrum antimicrobial activities, which include strong inhibitory and bactericidal effects, but also, they are excellent stimulators of plant growth (Jahanban & Mohammadreza, 2014; Biswal, Nayak, Parida & Nayak, 2012). Similarly, colloidal silver nanoparticles have proven to be effective fungicides against the rose powdery mildew caused by *Sphaerotheca pannosa Var rosae* (Biswal, Nayak, Parida & Nayak, 2012). Rose powdery mildew, a widespread disease that infect roses planted either in greenhouses or outdoors, can cause leaves distortion, curling of leaves, their early defoliation and flowering reduction. Utilization of double capsulized nanosilver could eliminate unwanted microorganisms in hydroponic systems and in planter soils. Furthermore, the use of nanosilver as foliar spray could potentially stop fungi, mold, rots, and several other plant-associated diseases (Jahanban & Mohammadreza, 2014).

Mesoporous silica nanoparticles

One of nanoparticles that have attracted scientific attention due to their capacity to target specific sites in plant by acting as magic bullets loaded with either herbicides, chemicals, or genes, are the mesoporous silica nanoparticles (MSNs). Compared to other nanoparticles, MSNs possess higher surface areas, higher pore volumes, better physiochemical stability, and highly ordered and homogenous pore network. Modification of surface properties of MSNs as well as their PEGylation made them perfect candidates for drugs delivery. MSNs can also deliver various hydrophilic or hydrophobic active agents. Nonetheless, high transfection rates have been recorded by chemically coating gene-loaded MSNs. Uptake of nanoparticles through cell walls can be prompted as a result of interactions between the chemical coating and cell walls (Srilatha, 2011).

Titanium oxide nanoparticles

Titanium oxide nanoparticles are described as non-toxic white pigments. titanium oxide nanoparticles can act as a strong disinfectant as compared to chlorine and ozone. Phytopathogenic disinfection efficiency of titanium oxide thin films have been improved by scientists via several methods such as dye doping. Application of titanium oxide nanoparticles as a photocatalyst, suited for plant photosynthesis enhancement, and have allowed a plant protection due to formation of toxic or dangerous compounds (Jahanban & Mohammadreza, 2014). Su *et al.* (2007), reported that evolution of oxygen in spinach plants could be improved with the use on nano-anatase titanium oxide. Krishna *et al.* (2006), recorded enhanced degradation of organic dyes, after combining titanium oxide nanoparticles with water soluble fullerenes, demonstrating a significant increasing in photocatalytic activity.

Nanocapsules

Nanoencapsulation is an innovative and promising nanotechnology in which agrochemicals are selectively, slowly, and efficiently released to a particular host plant. Nanoencapsulation can be applied in a wide range of fields in agriculture including the use of encapsulated nanoinsecticides for insect pest control, the use of nanoencapsulated pesticides for promotion of proper absorption of chemicals onto plants, and the use of nanoencapsulated DNA or chemicals for protection of host plants against insect pests (Prasad, Kumar & Prasad, 2014; Alam *et al.*, 2016). Different release mechanisms such as diffusion, dissolution, or biodegradation could be used for the delivery of agrochemicals in nanoencapsulated materials (Alam *et al.*, 2016).

Control of encapsulation

Exploitation of nanotechnology by agricultural and food agglomerates such as Monsanto, Syngenta, and Kraft enabled them to regulate the release of delivered substances through controlled and direct capsule manipulation (Chinnamuthu & Boopathi, 2009; Nichols, 2007). Researchers identified numerous encapsulation methods for smart nanoscale delivery systems such as surfactant micelles, vesicles, bilayers, reverse micelles, liquid crystals, liposomes, nano-emulsions, nano-lamination, colloids, biopolymeric nanoparticles, protein-carbohydrate nanoscale complexes, solid nano lipid particles, and dendrimers (Chena & Yadab, 2011; Biswal, Nayak, Parida & Nayak, 2012). The aforementioned encapsulation methods of desired substances have numerous benefits over conventional agricultural methods in that release kinetics is improved, better stability is provided against environmental stresses, better maintenance of high absorption and bioavailability is reached, and better provision of solubility and disperse-ability in aqueous based systems is achieved (Chena & Yadab, 2011).

Controlled release and delivery strategies of functional ingredients such as vaccines and agrochemicals are highly sought in medicine and agribusiness (Chinnamuthu & Boopathi, 2009; Biswal, Nayak, Parida & Nayak, 2012). Tremendous efforts and investments are geared up by agri-food and food companies to formulate, patent, and manufacture a variety of useful nano-formulations for pests, weeds, and insects control (Chinnamuthu & Boopathi, 2009).

Colloids

One encapsulation method is the colloid which is defined as a stable system containing tiny nanoparticles with a size ranging between 5 and 100 nm, dispersed in a liquid. Moreover, for many years the employment of some varieties of colloids such as association colloids in nanoencapsulation has facilitated the delivery of polar, nonpolar, and amphiphilic functional ingredients (Biswal, Nayak, Parida & Nayak, 2012).

Nano-emulsion

Another encapsulation method is nano-emulsion which is described as a complex system composed of two or more liquids that cannot be easily combined, are optically isotropic, and are kinetically a stable colloidal solution. Nano-emulsion can encapsulate droplets of functional ingredients with sizes as big as 500 nm and as small as 20 nm (McClements & Decker, 2000; Srilatha, 2011). Some companies utilize either water-based or oil-based nano-emulsions to encapsulate uniform suspensions of herbicidal or pesticidal nanoparticles. Through nano-emulsion, the incorporation of such particles in different media such as gels, creams, and liquids can be facilitated (Prasad, Kumar & Prasad, 2014). Nanoparticles in suspension are often physiochemically instable during their storage (Srilatha, 2011). Thus, water elimination from aqueous dispersions through the use of nano-emulsions can decrease chemical degradation of encapsulated droplets and nanoparticles nm (McClements & Decker, 2000; Srilatha, 2011). Furthermore, nano-emulsion is a potential encapsulation candidate for several applications in agri-food including the treatment and preservation of harvested products (Prasad, Kumar & Prasad, 2014).

Nano-lamination

Similar to food, nano-lamination is a practical method for harvested plants protection against perishing due to agents such as moisture accumulation and the presence of lipids and gasses (Biswal, Nayak, Parida & Nayak, 2012; Ali *et al.*, 2014). There are different methods to apply nanolaminates. One method is nano-coatings, which requires nanolaminates to be sprayed over food surface and plants. Predicala (2009), reported that nano-coatings could prevent weight loss and fruit shrinkage. Another method which requires food covering or plants with thin and food-grade protective films which are manufactured from edible polysaccharides, lipids, or proteins (Biswal, Nayak, Parida & Nayak, 2012; Ali *et al.,* 2014). Usually, between 1 and 100 individual nano-sized layers are combined to make one thin film (Biswal, Nayak, Parida & Nayak, 2012). Nanolaminate thin films have proven to be effectual barriers against gases such as carbon dioxide and oxygen (Ali *et al.*, 2014). In addition, lipid-based nanolaminates have proven to be successful in protecting food and plants against moisture (Biswal, Nayak, Parida & Nayak, 2012). Nanolaminates do not only preserve food and plants, but they can also improve the texture as well as preserve the flavor and color of the packaged food and plants (Biswal, Nayak, Parida & Nayak, 2012; Ali *et al.,* 2014).

Release mechanisms of nano-formulations

The study of the amount, rate, and release mechanisms of functional ingredients from inert materials such as nano-polymers has been a rapidly growing research field since the late 1960s and early 1970s (Ragaei & Sabry, 2014). Kratz, Narasimhan, Tangirala, Moon, Revanur, Kundu, Kim, Crosby, Russell, Emrick, Kolmakov & Balazs (2012), mentioned that the activity of nanoparticles is only initiated right after they are placed in a desired location. Therefore, nano-formulations must remain inactive until the active compound is released.

Chemical nature of nano-formulation is the primary determinant of how functional ingredient would likely be released. Primarily, a controlled release of functional ingredient proceeds through diffusion in a wide assortment of polymeric nanomaterials. Strength of chemical bonds in functional ingredient, its chemical properties, and its size regulate the release of the entrapped, encapsulated, or carried active compound (Mohammed & Sabry, 2014). Allan, Chopra, Neogi & Wilkins (1971), noted that chemical interaction involved in a controlled release of functional ingredient should be broken. Principally, the cessation of reaction occurs via hydrolysis reaction. However, Beasley & Collins (1970), showed that release of functional ingredient in some polymer matrices such as those made up from carboxylic acid and a metallic cation can be achieved when these polymers contact water.

Bioremediation

Environment protection, the reduction of pollution, and bioremediation could be accomplished through integration of nanotechnology into smart delivery systems, catalysts, and filters (Sertova, 2015). Expressly, microbial remediation has been dramatically influenced by nanotechnology advent (Dhewa, 2015). A wide range of nanomaterials which incorporate nanoscale zeolites, metal oxides, carbon nanotubes, carbon fibers, various other chemicals, noble metals such as bimetallic nanoparticles, and titanium oxide could be used in the field of bioremediation (Alam *et al.,* 2016; Power, Brown, Krishna, Wasdo, Moudgil & Roberts, 2006).

Smart delivery systems in bioremediation

Filtration of irrigation water

Bioremediation for the maintenance of environmental safety has been made possible with the use of smart delivery systems such as nanoparticles (Ditta, 2012). Bioremediation of harmful, resistant, or slowly degradable compounds in nature such as pesticides could be accomplished by using nanoparticles. Under certain conditions, nanoparticles would attach to harmful or toxic compounds, degrade them, and finally convert them into non-toxic compounds (Ditta, 2012; Dhewa, 2015). Unless these toxic or harmful compounds are removed from environment, they may negatively impact the health of animals, humans, and plants after they enter into food chain. One interesting application of smart delivery systems in bioremediation is the use of nanoparticle-water slurry. After a specific period of time, mixing of the aforesaid slurry with contaminated soil will result in a substantial decreasing in the toxicity of the slowly degradable or resistant pesticide (Dhewa, 2015). Another application of nanoparticles is manifest with the use of enzyme-based bioremediation in conjunction with phytoremediation. Polymers containing nanoparticles produced from metals or metal oxides could be used in environment remediation as well as used in catalysis, bio-separation, and drugs delivery (Sen, Prakash & Nirmal, 2015).

Utilization of different nanotechnology products such as nanomaterials for purification and filtration of irrigation water, could benefit farmers all over the world. Nano-enabled water treatment methods which employ membrane-based filters derived from carbon nanotubes, nano-porous ceramics, and magnetic nanoparticles are economic and effective alternatives for conventional water treatment methods (Prasad, Kumar & Prasad, 2014; NRC, 2008; Power *et al.*, 2006). Different methods have been developed for arsenic evacuation from drinking and irrigation water. Amongst the various cost-effective methods applied for this purpose include the use of engineered natural nano-minerals. Simply, water to be treated permeates through a section of hydrotalcite, which is an engineered mud mineral (Alam *et al.*, 2016). Furthermore, Gilman (2006), suggested that the previously mentioned technology could be improved and used in removal of organisms from drinking water in developing countries if coupled with draining through either permeable pots or filter candles.

The unique properties of magnetism could help farmers removed arsenic, metallic ions, and heavy metals from irrigation water (Chinnamuthu & Boopathi, 2009; Prasad, Kumar & Prasad, 2014). For instance, the use of magnetic nanoparticles could remove arsenic from irrigation water. Due to strong and irreversible interactions of nanocrystals such as monodisperse magnetite Fe_3O_4 with arsenic, at very low magnetic field gradients, removal of nanocrystals, which retains its magnetic properties, and arsenic from water could be achieved by using a simple handheld magnet (Prasad, Kumar & Prasad, 2014).

Likewise, researchers could create magnetic bacteria by adhering magnetic ions such as iron sulfonide, metallic ions and heavy metals such as iron sulphide precipitate onto the bacterial cell walls. Magnetic separation procedure of bacteria from irrigation water could be completed once bacteria become sufficiently magnetized. Other researchers revealed that iron-sulfonide-producing bacteria would absorb metallic ions from suspensions (Chinnamuthu & Boopathi, 2009). Another method for arsenic evacuation from irrigation water involves the use of zinc oxide nanoparticles. This method utilizes a point of decontamination gadget (Alam *et al.*, 2016).

Besides, filters containing nanoscale carriers and devices such as carbon nanotubes and carbon nanotubes-fused meshes are potent candidates for removal of contaminants, toxicants, water-borne pathogens, heavy metals such as lead, uranium, and arsenic from potable water (Prasad, Kumar & Prasad, 2014). Similarly, Argonide (2005), showed that entrapment of pathogenic viruses and bacteria as well as removal of microbial endotoxins, genetic materials, and micro-sized particles can be achieved via the use of sophisticated filtering machines employing nano-cream filters with positive charges.

Superfluous and continuous use of herbicides in farmlands would leave residue in soil, cause damage to succeeding crops, alter weed flora, and might lead to evolution of herbicide weed species resistant (Chinnamuthu & Boopathi, 2009). In developed countries, a wide collection of nanoparticles filters has been employed for remediation of waste sites. For example, remediation of toxins found in soil or groundwater can be attained with utilization of nanoscale zerovalent iron. Likewise, organic particles and pesticides such as DDT, endosulfan, malathion and chlor-pyrifos could be uprooted from water by using fabricated nanoparticle channels (Alam *et al.*, 2016).

Recycling of agricultural waste

The use of nanotechnology can help industries surmount difficulties which arise from the continuous disposal of agricultural wastes and byproducts during agricultural manufacturing of products such as cotton, rice, and beverages. Subsequently, these byproducts could be potentially used to manufacture valuable nanomaterials for bioremediation of agricultural farmlands. For instance, in cotton industry and after processing cotton, instead of discarding the byproducts such as cellulose or fibers, researchers identified new methods like electrospinning to use them in nanofibers production that have a size of 100 nm. The produced nanofibers can be used as high performance absorbents for bioremediation of fertilizers or pesticides (Dhewa, 2015).

Crop breeding

In agri-food industry, nanotechnology can be used to enhance nutritive properties and health-related benefits of crops and agricultural products (Dhewa, 2015). Similarly, bionanotechnology can improve plant traits and amplify their resilience against various environmental stresses such as drought, salinity, and diseases (Chena & Yadab, 2011). Moreover, recent studies revealed that quantities of vegetarian proteins, fats, and fibers found in Indian diets has experienced a sharp increasing as result of spraying zinc nanoparticles on crops (Dhewa, 2015).

Genetic manipulation of crops

Warad & Dutta (2005), noted the importance of finding new molecular and cellular tools in agri-food sector for separation, identification, and quantification of individual genes and molecules. Nonetheless, crop breeding has become a flexible task after nanotechnology introduction in agri-food sector (Sertova, 2015).

Likewise, crop breeding could be achieved using bionanotechnology which provides researchers with numerous tools to manipulate the genes of crops using nanoparticles, nanofibers, and nanocapsules (Argawal *et al.,* 2014; Sertova, 2015). For instance, nanofiber arrays can be used for drugs delivery, engineering crops via efficient and rapid delivery of genetic material to cells, and monitoring the environment. Also, the surface modification of carbon nanofibers with plasmid DNA could allow researchers to control biochemical manipulation in cells. Since fluorescent labelled starch-nanoparticles can bind genes, under the influence of ultrasound, they could be employed for genes transportation across plant cell walls through instantaneous pore channels in cell walls, cells membranes, and nuclear membranes (Argawal *et al.*, 2014). Additionally, Rad, Naderi, Alizadeh & Yaraghi (2013), mentioned that effective penetration of isolated protoplast of petunia and the transportation of plasmatic DNA while being incubated with ethylene glycol could be achieved by using treatments involving plasmid-coated Silver nanoparticles.

At the present time, extensive research is conducted for genome characterization in crops (Chena & Yadab, 2011). Prasanna & Hossain (2006), stated that both natural and induced mutations play an important role in crop breeding. In lieu of using conventional methods which utilize either chemical mutagens or physical mutagens such as X-rays or gamma rays, nanotechnology could prime the next frontier in mutagenesis-related research (Chinnamuthu & Boopathi, 2009). Moreover, Branton, Deamer, Marziali, Bayley, Benner, Butler, Di Ventra, Garaj, Hibbs, Huang, Jovanovich, Krstic, Lindsay, Ling, Mastrangelo, Meller, Oliver, Pershin, Ramsey, Riehn, Soni, Tabard-Cossa, Wanunu, Wiggin & Schloss (2008), documented that within a decade, the advancements in nanotechnology-enabled gene sequencing would create rapid and cost effective sequencing technologies.

Furthermore, delivery of genes to specific site at cellular level as well as rearrangement of atoms in DNA of the same organism to amplify the expression of desired traits could be accomplished using nanotechnology. Skipping of gene transfer from foreign organisms allows nanotechnology to consume less time than conventional gene transfer methods (Chinnamuthu & Boopathi, 2009). Nair, Varghese, Nair, Maekawa, Yoshida & Kumar (2010), and Gutiérrez, Mussons, Gatón & Rojo (2011), showed that priming of gene expression and release of genetic material throughout time in plants could be pursued by using properly functionalized nanomaterials loaded with various genes and substances. For example, PEGylated chitosan nanoparticles can control the release of genetic material throughout time (Nair et al., 2010; Gutiérrez, Mussons, Gatón & Rojo, 2011).

Nanotechnology supporters advocate the introduction of genetic engineering at atomic level in agri-food industry. Miller (2007), stated that atomically engineering crops could potentially allow industries to rearrange crops DNA to alter a wide variety of plant properties such as color, growth season, and yields. For example, by using nanotechnology, a new white-grained rice variety was produced from a traditional purple colored rice variety called Khao Kam by the Nuclear Physics Laboratory in Chiang Mai University in Thailand. Researchers used a particle beam to shot nitrogen atoms through previously drilled nano-sized holes in rice cell wall and membrane. Consequently, nitrogen atoms could stimulate the rearrangement of DNA of rice cells. Scientists and researchers call the organisms in which the DNA was altered at atomic level as atomically modified organisms (AMO) (Chinnamuthu & Boopathi, 2009).

Gene delivery systems

Scientists utilize various gene delivery systems in their research. One method for non-viral delivery of genes involves genes transportation vehicles called vectors. Vectors could either be polymers, biobeads or liposomes (Srilatha, 2011). First, gene transfer systems based on polymers which are influenced by ultrasound are the perfect alternative for viral transfection systems because the technique can be applied in restricted area and ultrasound energy is transmitted through the organism without damaging any tissue. Second, liposome based gene transfer systems offer many benefits over conventional gene transfer methods including an improved delivery of encapsulated DNA through membrane fusion and protection of nucleic acids from nucleases activity. Third, biobead based gene transfer systems are composed of micro-sized calcium alginate beads encapsulating plasmid DNA molecules that carry a reporter gene (Sen, Prakash, & Nirmal, 2015). Biobead based delivery systems has proven to be efficient transporters of plant genes with transfection rates as high as 0.22% recorded in protoplasts isolated from cultured tobacco cells (Srilatha, 2011).

A different method for the direct delivery of desired DNA in intact plant cells involves the use of gene gun or particle bombardment. Gold nanoparticles are used to deliver genes in this method primarily because they are not toxic to cells and they readily adsorb to DNA. The use of gene gun revealed positive results in transforming intact tobacco and maize tissues (Argawal *et al.* (2014). Conversely Nair *et al.* (2010), mentioned that in site targeted delivery and genes expression and chemicals right after the delivery of DNA and effector molecules is a major advantage of particle bombardment.

Nano-biosensors

Development of biosensors has lagged in the world of commerce despite the fact that biosensors have been around since glucose monitors commercialization in the 1970s. On the other hand, due to high sensitivity and rapid response time of electrochemical biosensors, which rely on effective immobilization of biomolecules without altering their bioactivity, their application has been growing exponentially (Srilatha, 2011). Various biosensors are available in market such as a rapid detection biosensors and enzymatic biosensors. In rapid detection biosensors, time required for microbial testing and immunoassays can be reduced. Such instruments have been used for contaminants detection in water bodies, food products, and food materials. In enzymatic biosensors, attachment of enzymes to certain biomolecules can act as a very specific sensing element (Ditta, 2012).

Moreover, nano-biosensors are modern sophisticated instruments that respond to physical, chemical, and biological stimulants and generate a useful output or signal that can be understood and utilized by humans (Prasad, Kumar & Prasad, 2014; Alam *et al.*, 2016). Need for the use of nano-biosensors might prove helpful for detection and identification of minute amounts of contaminants or stressors such as detection of foreign organisms, viruses, insect or pathogen pressure, toxins, biohazardous substances, drought, temperature, and the lack of nutrients in agri-food systems (Srilatha, 2011; Prasad, Kumar & Prasad, 2014; Alam *et al.*, 2016). Contemporary advancements in biosensors are opening the doors for agri-food industry to employ biosensors as screening tools in the analysis of fields and farmlands (Srilatha, 2011). Field sensing systems could provide keen intelligence on the status of moisture level, soil fertility, and weed presence (Chena & Yadab, 2011). Additionally, monitoring the status of nutrients or water over fine spatial and temporal scales could be effectively executed with the use of nanosenors, subsequently alerting farmers of any aberrations and allowing them to apply accurate quantities of supplements, water or agrochemicals. At last, better decisions can be made by farmers to increase crop yields and the efficiency of their agribusiness if they were aided by smart sensors (Prasad, Kumar & Prasad, 2014; Alam *et al.*, 2016).

Reduction of pollen contamination

Seeds production requires vigilance on behalf of producing industry to reduce pollen contamination especially in wind pollinated crops. Several factors such as air temperature, humidity, wind velocity, and pollen production of crops determine pollen flight. Application of nano-biosensors can ensure genetic purity of pollen by detecting any possible contaminants. Nano-biosensors could be also used to detect pollen produced by genetically modified crops (GMOs) and subsequently prevent them from contaminating field crops (Chinnamuthu & Boopathi, 2009; Argawal *et al.*, 2014).

Routine diagnosis of plant environment

A reaction involving soil solution and nanoproducts could be used for determination of accurate nutrient composition of soil (Chinnamuthu & Boopathi, 2009). Nanosenors developed for detection of pesticide residue could also be used to detect the level of soil moisture and soil nutrients (Sabir, Arshad & Chaudhari, 2014).

Early detection of plant diseases

Among the factors that limit the productivity of the crops are disease. Particularly, controlling viral diseases is a difficult task because they must be fought by using vectors. Nevertheless, the application of pesticides to crops once the crops start showing symptoms would be futile (Sertova, 2015). Henceforth, to achieve an effective control over pathogens and disease and maintain crop health, farmers could use miniaturize, portable, quick, sensitive, and accurate *in situ* sensors that can detect pathogens, contaminants, and pollutants (Dhewa, 2015). Alternatively, Joseph & Morrison (2006), stated that plant health identification issues before their symptoms become visible to farmers could be attained with the use of smart nanoscale agricultural systems. Prasanna & Hossain (2006), reported that diseases speed detection would be increased with the use of nano-based diagnostic kits. Moreover, development of nano-biosensors could aid agriculturists in determining the optimum amounts of agrochemicals such as pesticides and fertilizers to be used in farmlands (Sabir, Arshad & Chaudhari, 2014).

In addition, by using nanomaterials to create equipment exhibiting unique properties such small sizes, rapid responses, increased sensitivity, and low detection limits, nanosenors would allow farmers to detect pesticide residues and take adequate responses to changes in environment (Sabir, Arshad & Chaudhari, 2014; Sertova, 2015). Furthermore, researchers can trigger an electrical or chemical signal to detect the presence of contaminants such as bacteria in field conditions by introducing some improvements to nanoparticles or nano-surfaces (Sertova, 2015).

Nano-aptamers

Nano-aptamers are composed of single stranded nucleic acids which use the principle of targeted and specific binding with high affinity. Sensors utilizing nano-aptamers could give rise to a new generation of tools that detect plant diseases and crop resistances, as well as monitor crop yields. Instead of distressing cells, a sensor that monitors cell-to-cell signaling can be installed along with a photoluminescence target specific device. For instance, a sensor containing insulin-binding nano-aptamers were manufactured to monitor extinction of lights from cells to get the signal. At last, concerning the assessment of food safety due to the use of herbicides and pesticides in crop production, an efficient nano-aptamer sensor was devised to monitor toxicity level in food with luminescent assay technique (Sabir, Arshad & Chaudhari, 2014).

Nano-chips

López, Llop, Olmos, Noales, Cambra & Bertolini (2009), identified nano-chips as a type of microarrays containing oligo capture probes capable of detecting the hybridization. Nano-chips can detect single nucleotide changes of bacteria and viruses with high sensitivity and specificity. Yao *et al.* (2009), reported a successful attempt to detect *Xanthomonas axonopodis pv. vesicatoria,* which causes bacterial spot disease in Solanaceae plants, by using fluorescence silica nanoparticles in conjunction with antibodies. Moreover, Karnal bunt disease detection in wheat was accomplished by Singh, Manoj, Ved & Kumar (2010), by using nano-gold based immune-sensors and Surface Plasmon Resonance (SPR).

Nanofertilizers

Since fertilizers are considered to be a major player in crop production, there is a rising need to overcome chronic problems of eutrophication and enhance the nutrient use efficiency. Although technology of nanofertilizers is innovative, scant literature is reported (Alam *et al.*, 2016). However, the utilization of nanofertilizers in agriculture can surmount the previously mentioned difficulties (Prasad, Kumar & Prasad, 2014; Alam *et al.,* 2016). Unlike conventional chemical fertilizers, nanofertilizers do not only act as fertilizers, but they also have the potential to revive soil to an organic state without harmful effects, reduce nitrogen loss due to leaching, allow selective release of active compound under certain environmental conditions, increase crop yields, and enhance photosynthesis (Prasad, Kumar & Prasad, 2014; Sabir, Arshad & Chaudhari, 2014; Alam *et al.,* 2016). Moreover, since small amounts of nanofertilizers are enough to exert their effect in farmlands, the frequency of applying nano-fertilizers could be decreased (Sabir, Arshad & Chaudhari, 2014; Alam *et al.*, 2016). For instance, treatment of wheat plant seeds with meal nanoparticles lead to an average increase by 20 to 25% in their yields (Sabir, Arshad & Chaudhari, 2014). Furthermore, application of SiO_2 and TiO_2 nanoparticles in soybean increased the activity of nitrate reductase and increased water efficiency and fertilizer use (Alam *et al.*, 2016).

Nanopesticides

Nanoparticles exhibit pesticidal, insecticidal effects and are effective repellents of insects (Alam *et al.,* 2016). Bergeson (2010), indicated that reduction in organic solvent runoff could be possible with use of nanopesticides. Similarly, Bouwmeester, Dekkers, Noordam, Hagens, Bulder, de Heer, Ten Vorde, Wijnhoven, Marvin & Sips (2009), reported that useful properties such as stiffness, permeability, crystallinity, thermal stability, solubility, and biodegradability exhibited by nanomaterials and biocomposites could ease nanopesticides formulation. Efficient delivery of water-soluble pesticide and its subsequent controlled release could be achieved with the use of porous hollow silica nanoparticles (PHSNs) loaded with a pesticide called validamycin (Alam *et al.*, 2016). A more complex method to formulate nanopesticides is through encapsulating them within a shell. Employing this approach has prompted revolutionary changes in agri-food industry, mainly because researchers have the ability to program capsules or shells to release their active ingredients if certain conditions were satisfied. Scientists are interested in nanopesticides encapsulation due to its various advantages such as extended patent protection, an increased solubility, and reduced contact of active ingredients with workers and farmers (Chinnamuthu & Boopathi, 2009). Another two effective methods to formulate nanopesticides is nano-emulsion and the use of oil-loaded solid lipid nanoparticles (Alam *et al.*, 2016).

Nanoinsecticides

Nano-silica is not only useful as a nanopesticides, but as Barik, Sahu & Swain (2008), reported that can also be effectively used as a nanoinsecticide. Because insect pests use a wide variety of cuticular lipids to protect their water barrier, consequently averting the possibility of their death from desiccation, nano-silica particles can circumvent the above-mentioned difficulty of being absorbed directly by cuticular lipids. Additionally, utilization of polyethylene glycol-coated nanoparticles, which are loaded with garlic essential oil has resulted in 80% control efficacy of *Tribolium castaneum* insect due to slow and persistent release of functional ingredients from nanoparticles. Significant mortality rates against two persistent insect pests found in stored food supplies, *viz. S. oryzae L. and Rhyzopertha dominica (F.)*, were recorded after 3 days of exposure to nanostructured alumina treated wheat (Alam *et al.*, 2016).

Micro-fabricated xylem-vessels

The advent of new innovative nanotechnologies in fields of plant pathology, nano-fabrication, and characterization of tools have allowed researchers to easily understand physical, chemical, and biological interactions between plant cells and pathogens. Cursino, Li, Zaini, De La Fuente, Hoch & Burr (2009), stressed that as scientists gain more knowledge pertained to various interaction of plant pathogenic mechanisms such as flagella motility and biofilms, development of diagnostic methods and improved treatments for many diseases could be facilitated.

Moreover, advancements in nanotechnology have allowed scientists to surmount difficulties of traditional strategies to study plant pathogen interactions by facilitating the micro-fabrication of xylem vessels with nano-sized features (Ditta, 2012, Dhewa, 2015). For instance, earlier techniques to study xylem-inhibiting bacteria involved the use of destructive sampling techniques at different distances from inoculation sites. However, because the sample site cannot be followed temporally, traditional strategies suffered from major drawbacks in the amount of collected information, particularly those related to colonization, biofilm development, and recolonization at new areas (Chena & Yadab, 2011; Ditta, 2012). Zaini DeLa, Fuente, Hoch & Burr (2009) documented that employment of micro-fabricated xylem vessels can aid scientists in understanding bacterial colonization in xylem vessels and in developing new disease control strategies.

Smart Nano-dust

Uniform scattering and distribution of innumerable number of nano-sensors over farmlands like dust will act in the future as smart eyes, ears, and noses of farming industrial complex. Through utilization of smart dust, many parameters such as temperature, humidity, nutrient deficiencies, insect infestations, and disease infestations can be sensed, detected, and monitored. Smart nano-dust particles or nano-sensors, which are connected to global positioning system (GPS), would be able to operate autonomously, communicate wirelessly information they collect, and sense in real time as well as respond rapidly to any variations in aforementioned parameters. This complex intelligence network of smart particles or sensors can warn farmers in advance to devise ways to deal with any aberrations in environment. Additionally, employment of smart dust systems can help farmers evaluate the amount of pollutants in environment (Ditta, 2012; Ali *et al.*, 2014).

Risk assessment of nanotechnology in agri-food sector

Utilization of nanotechnology products such as nanoparticles entails some potential risks that are no different than those present in any other industry (Biswal, Nayak, Parida & Nayak, 2012). Despite various benefits of using nanoparticles and nanomaterials, their industrial application give rise to new forms of hazards to environment and people (Scrinis & Lyons, 2007). For instance, harmful effects which include the damage of tissue that could reach vital organs have been recorded in studies that used nanomaterials (Rameshaiah, Pallavi & Shabnam, 2015). A leading environmental group called the group ETC which stands for action group on erosion, technology, and concentration, are concerned that merging nanotechnology and biotechnology has a number of unknown consequences for health, biodiversity, and environment (Biswal, Nayak, Parida & Nayak, 2012). Although there is a very scant literature documenting health effects of eating nano-particles or workers handling nanomaterials, the British royal society has issued a warning of the serious risks of nano-toxicity (Scrinis & Lyons, 2007).

Several negative effects such as damage of membranes, reduction in annual growth of grass, and depletion of photosynthesis in the algae *Chlamydomonas reinhardtii* have been caused by the use of silver nanoparticles as nanofertilizers. A key concern of watchdog groups is an infiltration of nanoscale particles of the body through inhalation, digestion, and skin could pass them into bloodstream, penetrate cells, by-pass immune responses, lodge in the lungs, and cross the blood-brain barrier (Rameshaiah, Pallavi & Shabnam, 2015). At last, general public is ought to participate in debates pertained to the use of nanotechnology in agri-food systems. Their active participation and engagement is crucial for dealing with adverse effects and repercussion of nanotechnology as well as assessing the risks involved and defining measures to be undertaken to resolve these risks (Scrinis & Lyons, 2007).

Perpetual advancements in nanotechnology would enable farmers to efficiently use water and agrochemicals as well as detect pathogens, analyze soil quality, and monitor plant health (Sekhon, 2014). Despite holding more potential than GM, nanotechnology may entail huge risks. The lack of organized definitions, statutory regulations, and defined methods in nanotechnology hampers risk assessment (Jahanban & Mohammadreza, 2014). Therefore, is imperative for researchers and scientists to create international standards for nanotechnology. Similarly, for reduction of number of different risk assessments of nanotechnology among countries, the international scientific community is ought to establish a special international organization whose governance is peculiar to field of nanotechnology (Moskvins *et al.*, 2012).

References

Adzmi, F., Meon, S., Musa, H.M. & Yesuf, N. (2012). Preparation, Characterization and Viability of encapsulated Trichoderma harzianum UPM 40 in alginate- montmorillonite clay. *J Microencapsul*, 29(3), 205-210. *http://dx.doi.org/10.3109/02652048.2012.659286*

Agrawal, S. & Rathore, P. (2014). Nanotechnology Pros and Cons to Agri-food: A Review. *Int J Curr Microbiol App Sci*, 3(3), 43-55. *https://www.ijcmas.com/vol-3-3/Shweta%20Agrawal%20and%20Pragya%20Rathore.pdf.*

Alam, A.R., Ismat, F., Sayeed, K., Khan, A., Akhtar, S., Farooqui, A. & Siddiqui, M.H. (2016). Applciation of nanotechnology in agri-food and food science. *World J Pharm Sci*, 4(7), 45-54. *http://www.wjpsonline.org/admin/uploads/Oc52t6.pdf.*

Ali, M.A., Rehman, I., Iqbal, A., Din, S.U., Rao, A.Q., Latif, A., Samiullah, T.R., Azam, S. & Husnain, T. (2014). Nanotechnology, A New Frontier in Agri-food. *Int J Adv life sci*, 1(3), 129–138. *http://www.als-journal.com/articles/vol1issue3/Nanotechnology_new_frontier_agri-food.pdf.*

Allan, G.G. Chopra, C.S. Neogi, A.N. & Wilkins, R.M., (1971). Design and synthesis of controlled release pesticide-polymer combinations. *Nature*, 234(5328), 349-351. *http://dx.doi.org/10.1038/234349a0*

Barik, T.K. Sahu, B. & Swain, V. (2008). Nanosilica-from medicine to pest control. *Parasitol Res*, 103(2), 253-258. *https://doi.org/10.1007/s00436-008-0975-7*

Beasley, M.L. & Collins, R.L. (1970). Water-degradable polymers for controlled release of herbicides and other agents. *Science*, 169 (3947), 769-770. *https://doi.org/10.1126/science.169.3947.769*

Bergeson, L.L. (2010) Nanosilver: US EPA's pesticide office considers how best to proceed. *Environ Qual Manage*, 19(3), 79–85. *https://doi.org/10.1002/tqem.20255*

Biswal, S. K., Nayak, A.K., Parida, U.K. & Nayak, P. L. (2012). Applications of nanotechnology in agri-food and food sciences. *Int J Sci Innov Discov*, 2(1), 21-36. *http://www.ijsidonline.info/admin/pdf_files/0201_2012_review003.pdf.*

Bouwmeester, H., Dekkers, S., Noordam, M.Y., Hagens, W.I., Bulder, A.S., de Heer, C., Ten Vorde, S.E.C.G., Wijnhoven, W.P., Marvin, H.J.P. & Sips, A.J.A.M. (2009). Review of health safety aspects of nanotechnologies in food production. *Regul Toxicol Pharmacol*, 53(1), 52–62. *https://doi.org/10.1016/j.yrtph.2008.10.008*

Branton, D., Deamer, D.W., Marziali, A., Bayley, H., Benner, S.A., Butler, T., Di Ventra, M., Garaj, S., Hibbs, A., Huang, X., Jovanovich, S.B., Krstic, P.S., Lindsay, S., Ling, X.S., Mastrangelo, C.H., Meller, A., Oliver, J.S., Pershin, Y.V., Ramsey, J.M., Riehn, R., Soni, G.V., Tabard-Cossa, V., Wanunu, M., Wiggin, M. & Schloss, J.A. (2008). The potential and challenges of nanopores sequencing. *Nat Biotechnol*, 26, 1146-1153. *https://doi.org/10.1038/nbt.1495*

Chen, H., Weiss, J. & Shahidi, F. (2006). Nanotechnology in Nutraceuticals and Functional Foods. *Food Tech*, 60(3), 30-36. *http://library.wur.nl/WebQuery/file/cogem/cogem_t45017dfd_001.pdf.*

Chena, H. & Yadab, R. (2011). Nanotechnologies in Agri-food: New tools for sustainable development. *Trends Food Sci Tech*, 22(11), 585-594. *https://doi.org/10.1016/j.tifs.2011.09.004*

Chinnamuthu, C.R. & Boopathi, P.M. (2009). Nanotechnology and Agroecosystem. *Madras Agricultural Journal*, 96(1-6), 17-31.

Cursino, L., Li, Y., Zaini, P. A., De La Fuente, L., Hoch, H. C., & Burr, T. J. (2009). Twitching motility and biofilm formation are associated with tonB1 in *Xylella fastidiosa*. *FEMS Microbiol Lett*, 299(2), 193-199. *https://doi.org/10.1111/j.1574-6968.2009.01747.x*

Dhewa, T. (2015). Nanotechnology applications in agri-food: an update. *Octa J Environ Res*, 3(2), 204-211. *http://sciencebeingjournal.com/sites/default/files/10-150316_0302_TPD.pdf.*

Ditta, A. (2012). How helpful is nanotechnology in agricultur?. *Adv Nat Sci: Nanosci Nanotechnol*, 3(3), 3-5. *https://doi.org/10.1088/2043-6262/3/3/033002*

Gilman, G.P. (2006). A simple device for arsenic removal from drinking water using hydrotalcite. *Sci Total Environ*, 366(2-3), 926–931. *https://doi.org/10.1016/j.scitotenv.2006.01.036*

Gutiérrez, F.J. Mussons, M.L. Gatón, P. & Rojo, R. (2011). Nanotechnology and Food Industry. *Scientific, Health and Social Aspects of the Food Industry*. Chapter 6. pp. 95-128. Benjamin Valdez (Eds.). *https://doi.org/10.5772/33458*

Jahanban, L. & Mohammadreza, D. (2014). Organic Agri-food and Nanotechnology. Rahmann, G. & Aksoy, U. (Eds.) (2014). Proceedings of the 4th ISOFAR Scientific Conference.'Building Organic Bridges', at the Organic World Congress 2014, 13-15 Oct., Istanbul, Turkey. *http://orgprints.org/23620/1/23620_MM.pdf.*

Jayaseelan, C. Rahuman, A.A. Rajakumar, G. Vishnu, A.K. Santhosh, T. Marimuthu, S. Bagavan, A. Kamaraj, C. Zahir, A.A. & Elango, G. (2011). Synthesis of pediculocidal and larvicidal silver nanoparticles by leaf extract from heartleaf moonseed plant, Tinospora cordifolia Miers. *Parasitol Res*, 109(1), 185-194. *https://doi.org/10.1007/s00436-010-2242-y*

Joseph, T. & Morrison, M. (2006). Nanotechnology in Agri-food and Food. A Nanoforum Report. Institute for Nanotechnology. European Nanotechnology Gateway (Eds.).14 p. *ftp://ftp.cordis.europa.eu/pub/nanotechnology/docs/nanotechnology_in_agri-food_and_food.pdf.*

Kratz, K., Narasimhan, A., Tangirala, R., Moon, S.C., Revanur, R., Kundu, S., Kim, H.S., Crosby, A.J., Russell, T.P., Emrick, T., Kolmakov, G. & Balazs, A.C. (2012). Probing and repairing damaged surfaces with nanoparticle-containing microcapsules. *Nat Nanotechnol*, 7, 87-90. *https://doi.org/10.1038/nnano.2011.235*

López, M.M., Llop, P., Olmos, A., Noales, E., Cambra, M. & Bertolini, E. (2009). Are molecular tools solving the challenges posed by detection of plant pathogenic bacteria and viruses?. *Curr Issues Mol Biol*, 11(1), 13-46. *https://doi.org/10.21775/cimb.011.013*

Manimaran, M. (2015). A review on nanotechnology and its implications in agri-food and food industry. *Asian J Plant Sci Res*, 5(7), 13-15. *http://www.imedpub.com/articles/a-review-on-nanotechnology-and-its-implications-in-agri-food-and-food-industry.pdf.*

Manjunatha, S.B., Biradar, D.P. & Aladakatti, Y.R. (2016). Nanotechnology and its applications in agri-food: A review. *J Farm Sci*, 29(1), 1-13. *http://14.139.155.167/test5/index.php/kjas/article/viewFile/7890/8148.*

McClements, D. J. & Decker, E. A. (2000). Lipid Oxidation in oil-in water emulsions: impact of molecular environment on chemical reactions in heterogeneous food systems. *J Food Sci*, 65(8), 1270-1282. *https://doi.org/10.1111/j.1365-2621.2000.tb10596.x*

Miller, G. (2007). Nanotechnology the new threat to food. Clean Food Organic. Friends of the Earth (Eds.). Nanotechnology Project. *http://emergingtech.foe.org.au/198/.*

Moskvins, G., Spakovica, E., Moskvins, A., Shakhtarina, A. & Beldavs, V. (2012). Development of nanotechnology in agri-food for small northern European country. *Engineering for Rural Development*, 24, 157-163. *http://tf.llu.lv/conference/proceedings2012/Papers/027_Moskvins_G.pdf.*

Murphy, K. (2008). Nanotechnology: Agri-food's Next Industrial Revolution. pp 3–5. Williston, VT: Financial Partner, Yankee Farm Credit, ACA (Eds.). Spring.

NAAS, (2013). Nanotechnology in agri-food: Scope and Current Relevance. Policy Paper No. 63. National Academy of Agricultural Sciences, New Delhi: 20 p.

Nair, R. Varghese, S.H. Nair, B.G. Maekawa, T. Yoshida, Y. & Kumar, D.S. (2010). Nanoparticulate material delivery to plants. *Plant Sci*, 179(3), 154 163. *https://doi.org/10.1016/j.plantsci.2010.04.012*

Narayanan, A., Sharma, P. & Moudgil, B.M. (2013). Applications of engineered particulate systems in agri-food and food industry. *KONA*, 30 (2013), 221-235. *https://doi.org/10.14356/kona.2013021*

Nichols, R.S.M. (2007). Nanotechnology: Implications for Food and Nutrition professionals. *J Am Diet Assoc*, 107(9), 1494-1497. *https://doi.org/10.1016/j.jada.2007.06.016*

Nowack, K. & Speiser, B. (2008). Discussion paper on the use of nanotechnologies in organic production. Research Institute of organic Agri-food, Switzerland, 1-7. *http://www.betriebsmittelliste.ch/fileadmin/documents/de/hifu/stellungnahmen/discussionpaper_nanotechnology.pdf.*

NRC- National Research Council. (2008) Emerging technologies to benefit farmers in sub-Saharan Africa and South Asia, National Academic Press (Eds.), Washington, D.C., United States of America. *http://nas-sites.org/ag-technologies/files/2012/12/52606862-Farmers-in-Sub-Saharan-Africa-and-South-Asia-Report-in-Brief.pdf.*

Patil, S.A. (2009). Economics of Agri Poverty: Nano-Bio Solutions, Indian Agricultural Research Institute, New Delhi, India.

Power, K.W., Brown, S.C., Krishna, V.B., Wasdo, S.C., Moudgil, B.M. & Roberts, S.M. (2006). Research strategies for safety evaluation of nanomaterials. Part VI. Characterization of nanoscale particles for toxicological evaluation. *Toxicol Sci*, 90(2), 296-303. *https://doi.org/10.1093/toxsci/kfj099*

Prasad, R., Kumar, V. & Prasad, K. S. (2014). Nanotechnology in sustainable agri-food: present concerns and future aspects. *Afr J Biotechnol*, 13(6), 705-713. *https://doi.org/ 10.5897/AJBX2013.13554*

Prasanna, B. & Hossain, F. (2006). Nanotechnology in agri-food. *Pusa Agriscience*, 29, 7-1.

Predicala, B., (2009). Nanotechnology: potential for agri-food, Prairie Swine Centre Inc (Eds.). University of Saskatchewan, Saskatoon, Canada. 138p.

Rad, S.J. Naderi, R. Alizadeh, H. & Yaraghi, A.S. (2013). Silver-nanoparticle as a vector in gene delivery by incubation. *Int Res J Appl Life Sci*, 2(3), 21-33.

Ragaei, M. & Sabry, A. H. (2014). Nanotechnology for Insect Pest Control. *International Journal of Science, Environment and Technology*, 3(2), 528-545. http://www.ijset.net/journal/279.pdf.

Rameshaiah, G. N., Pallavi, J. & Shabnam, S. (2015). Nano fertilizers and nano sensors – an attempt for developing smart agri-food. *Int J Eng Res Gen Sci*, 3(1), 314–320. *http://pnrsolution.org/Datacenter/Vol3/Issue1/40.pdf.*

Ravichandran, R. (2010). Nanotechnology applications in food and food processing: innovative green approaches, opportunities and uncertainties for global market. *Int J Green Nanotechnol: Phys Chem*, 1(2), 72-96. *https://doi.org/10.1080/19430871003684440*

Sabir, S., Arshad, M. & Chaudhari, S. K. (2014). Zinc Oxide Nanoparticles for Revolutionizing Agri-food: Synthesis and Applications. *Sci World J,* 2014 (2014). *http://dx.doi.org/10.1155/2014/925494*

Samantarai, S.K. & Achakzai, A.K.K. (2014). Applications of nanotechnology in agri-food and food production: opportunity and challenges. *Middle East J Sci Res*, 22(4), 499-501. *http://dx.doi.org/10.5829/idosi.mejsr.2014.22.04.21920*

Scrinis, G. & Lyons, K. (2007). The emerging nano-corporate paradigm: nanotechnology and the transformation of nature, food and agri-food systems. *Int J Sociol Food Agric*, 15(2), 22–44. *http://www.ijsaf.org/archive/15/2/scrinis_lyons.pdf.*

Sekhon, B. S. (2014). Nanotechnology in agri-food production: an overview. *Nanotechnol Sci Appl*, 7, 31-53. *http://dx.doi.org/ 10.2147/NSA.S39406*

Sen, J. Prakash, P. & Nirmal, D. (2015). Nano-clay composite and phyto-nanotechnology: a new horizon to food security issue in Indian agri-food. *J Global Biosci*, 4(5), 2187–2198. *http://www.mutagens.co.in/jgb/vol.04/5/12.pdf.*

Sertova, N. (2015). Application of nanotechnology in detection of mycotoxin and in agricultural sector. *J Central Eur Agric*, 16(2), 117-130. *http://dx.doi.org/10.5513/jcea.v16i2.3472*

Singh, S. S., Manoj, A., Ved, V. & Kumar, A. (2010). An attempt to develop surface plasmon resonance based immunesensor for Karnal Bunt (*Tilletia indica*) diagnosis based on the experience of nano-gold based lateral flow immune-dipstick test. *Thin Solid Films*, 519(3), 1156-1159. *http://npl.csircentral.net/21/1/12.pdf.*

Srilatha, B. (2011). Nanotechnology in Agri-food. *J Nanomedic Nanotechnol*, 2 (7), 123-128. *http://dx.doi.org/10.4172/2157-7439.1000123*

Su, M., Wu, Y., Liu, C., Qu, C.X., Liu, X.Q., Chen, L., Huang, H. & Hong, F.S. (2007). Promotion of energy transfer and oxygen evolution in spinach photosystem II by nano-anatase TiO_2. *Biol Trace Elem Res*, 119(2), 183-192. *http://dx.doi.org/10.1007/s12011-007-0065-1*

Warad, H.C. & Dutta, J. (1995). Nanotechnology for agri-food and food systems-a view. Asian Institute of Technology, School of Advanced Technologies, Thailand, 1-14.

Yang, F.L., Li, X.G., Zhu, F. & Lei, C.L. (2009). Structural characterization of nanoparticles loaded with garlic essential oil and their insecticidal activity against Tribolium castaneum (Herbst) (Coleoptera: Tenebrionidae). *J Agric Food Chem*, 57(21), 10156-10162. *http://dx.doi.org/10.1021/jf9023118*

Yao, K.S., Li, S.J., Tzeng, K.C., Cheng, T.C., Chang, C.Y., Chiu, C.Y., Liao, C.Y., Hsu, J.J. & Lin, Z.P. (2009). Fluorescence silica nanoprobe as a biomarker for rapid detection of plant pathogens. *Adv Mater Res*, 79-82, 513-516. *http://dx.doi.org/10.4028/www.scientific.net/AMR.79-82.513*

Zaini, P. A., De La Fuente, L., Hoch, H. C. & Burr, T. J. (2009). Grapevine xylem sap enhances biofilm development by *Xylella fastidiosa*. *FEMS Microbiol Lett,* 295(1), 129-134. *http://dx.doi.org/10.1111/j.1574-6968.2009.01597.x*

Zimdahl, R.L. (1999). Fundamentals of Weed Science. 3rd Edition. Academic Press (Eds.). London, United Kingdom. 689p. *http://base.dnsgb.com.ua/files/book/Agri-food/Weed/Fundamentals-of-Weed-Science.pdf.*