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The use of nanotechnology in the agriculture

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Abstract. Nanotechnology is considered the most important technological advancement in recent years, and it is utilized in all industries due to its potential applications. Almost all of the industries (food, agriculture, medicine, automotive, information and communication technologies, energy, textile, construction, etc.) reorganize their future in the light of nanotechnological developments. As the most important source of income of countries, the agriculture industry increases the use of nanotechnology products gradually as a solution to the problems encountered. Reducing the use of agricultural inputs (pesticides, herbicides, fertilizers, etc.) by increasing their efficiency utilizing nano-carriers, detecting the environmental conditions and development of the crops in the field simultaneously by making use of nanosensors, reducing the sample volume and the amount of analyte used thanks to nanoarrays, effective treatment of water resources through nano-filters, accelerating the development of crops by using nanoparticles are the prominent nanotechnological applications in the agriculture industry. This review presents information on the benefits of the recent developments in nanotechnology applications in the agriculture industry.

Keywords: agriculture; nanobiotechnology; nano-fertilizers; nano-pesticides; nanobiosensors

1. Introduction

The nano- prefix was derived from a Greek word “nannos”, meaning “dwarf”, and refers to one billionth of a physical dimension. The nanometer term corresponds to one billionth of a meter (1 nm=10^{-9} m) (Navrotsky *et al*. 2000, Huang *et al.* 2007). The term nanotechnology is a science on the manipulation and engineering of nano-scale materials up to 1-100 nm in size (Dudo *et al.* 2011, Ehsani *et al.* 2012). The focus is on the nanotechnology, among the recent technological developments. Nanotechnology has a wide range of applications used in agriculture, medicine, chemistry, physics, food industry, energy, telecommunications, textiles, electronics, sporting goods, construction industry, energy and automotive industry etc. (Qureshi *et al.* 2009, Bradlay *et al.* 2011, Zambrano-Zaragoza *et al.* 2011, Rai and Ingle 2012, Fakruddin *et al.* 2012, Ditta *et al.* 2015).

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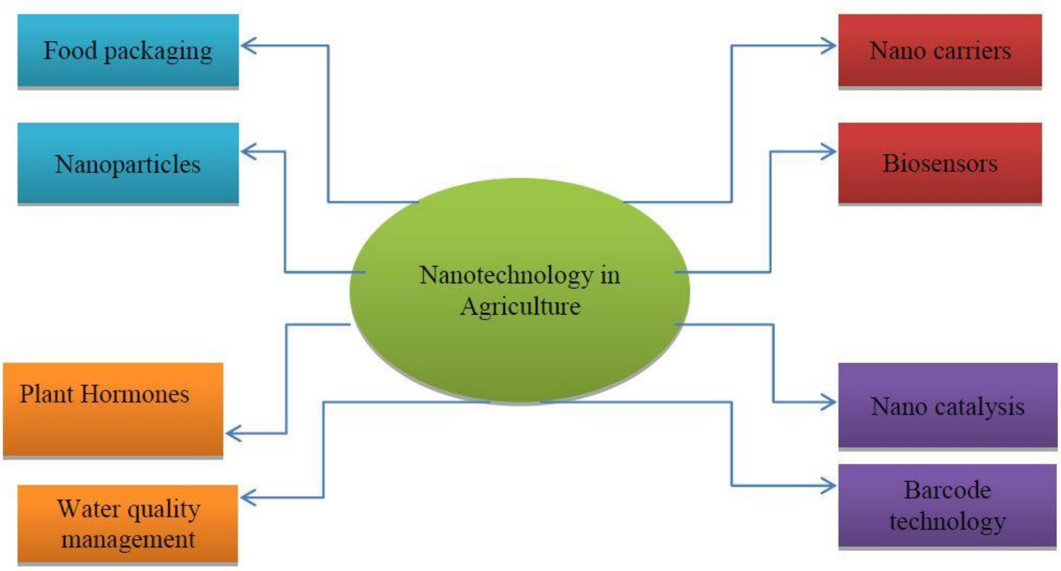

Fig. 1 Fields of nanotechnological studies in agriculture

In terms of countries, the agriculture industry is the building block of the economy, where livelihood of more than 60% of the population of the world depends on directly or indirectly (Brock *et al.* 2011, Qamar *et al.* 2014). However, sustainable agriculture fields have been decreasing due to use of excessive fertilizer, pesticide, herbicide, improper irrigation techniques, environmental factors such as climatic changes, etc. Therefore, a technology that can shape the modern agriculture is needed in the agriculture industry for cost-efficient better production by providing the right amount of input at the right time (Prasad *et al.* 2012). Having a significant role in recent technological developments, the nanotechnology can be used in remodeling the agriculture and food production in order to meet the demands in a cost-effective way.

Although the nanotechnology studies and utilization of nanotechnology in the agriculture industry were late compared to other industries, the use of nanotechnology gains momentum in this sector increasingly. Nanotechnology applications in the agriculture industry is possible by the use of precision agriculture techniques (remote and local sensing), improvement (water treatment plants, removal of pesticides in the groundwater), nano-sensors, nano-agricultural chemicals, and design of the intelligent distribution systems (nano-carriers) for pesticides and nutrients, nano barcode, food packaging (Scrinis and Lyons 2007, Ditta *et al.* 2015, Ditta and Arshad 2015) (Fig. 1). This article presents an evaluation of the data on nano-pesticides, nano-herbicides, nanosensors, and some other studies conducted on the current and potential applications of nanotechnology in the agriculture industry.

2. Location of nanobiotechnology in agriculture

2.1 Nano-sized carriers

These are ‘smart’ nanoscale carriers that can be used for effective and efficient distribution of

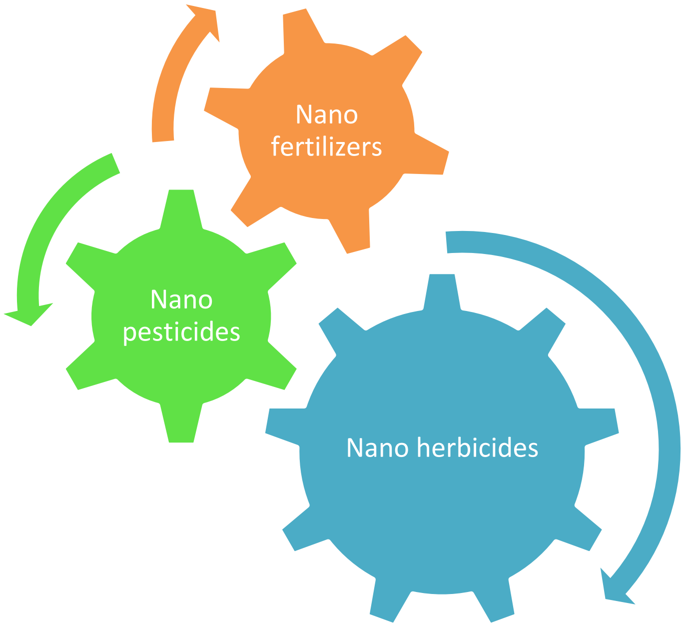

Fig. 2 Nano carriers in agriculture industry

fertilizers, herbicides, pesticides and plant growth regulators. Nanoscale carriers are designed to be attached to plant roots in the organic material and surrounding soil. That way, it becomes possible to enhance stability and reduce the amount of inputs to be used by preventing a deformation induced by environmental factors (Johnston 2010, Ditta 2012, Kumar *et al*. 2014, Ramalingam *et al*. 2015).

2.1.1 Nano-fertilizers

Plants need some essential elements for growth and living. Nitrogen, phosphate, potassium, calcium, magnesium, sulfur, iron, manganese, zinc can be listed among these necessary elements. Most of these elements are found in soil, however they are not sufficient in some cases for the plant growth. In this case, the manufacturers use fertilizers that include the elements necessary for the plant growth.

And, as a result of unconscious over-fertilization, only the 50% of fertilizer is utilized by plants, and the rest is removed by evaporation or irrigation from the soil. The fertilizers removed from the soil that way may cause adverse effects to the people, animals and environment. Excessive use of fertilizers increases the accumulation of pollutants in the soil, and consequently leads to imbalance of the elements present in the soil, breakdown of soil reaction, decrease in the crop production potentials, low quality, and the long-term serious health problems in humans and animals fed with the nutrients and forage that accumulates toxic substances (Ditta and Arshad 2015).

Advances in nanotechnology offer significant advantages to minimize these negative properties of fertilizers; fertilizer carriers, which are called as smart fertilizers, or the nanosized materials as the tools of controlled release increase the effectiveness of fertilizer used and hence reduce the amount significantly. In this way, the pollution from fertilizers is minimized in soil, water resources and in food products. Thanks to the high surface to volume ratio, which is one of the most important features of nano-materials, the nano-fertilizers can be easily taken by plants due to a more efficient contact. Reduction of the frequency and amount of fertilizer application has an economic benefit as a result of the decreased fertilizer and labor costs. Compared to commercial fertilizers, the nano-fertilizers lead to a higher increase in product yield. The fertilizer loss caused by elution and evaporation in the soil system is minimized with the use of nano-sized materials. The nutrients retain their activity in the soil longer thanks to nano-fertilizers (Cui *et al.* 2010, De Rosa *et al.* 2010, Naderi *et al.* 2013, Ditta *et al*. 2015, Ditta and Arshad, 2015).

Wu *et al*. (2008) improved a chitosan-coated NPK composition fertilizer with both controlled-release and water-retention abilities, by using an inner coating of chitosan, and an outer coating was poly (acrylic acid-co acrylamide) (P(AA-co-AM)). It was viewed that the prod-uct indicated a slow controlled release of the nutrients. The nutrients released did not exceed 75% on the 30th day. Moreover, chitosan is a readily biodegradable product, while the *P*(AA-co-AM) can also be degraded in soil, so neither the matrix polymers nor their degraded products were destructive to the soil.

In a study by Liu *et al*. (2009), nano-calcium carbonate was compared with humic acid, and organic fertilizer in groundnut, and reported that at low concentrations the nano-calcium carbonate leads to an increase in the number of leaves and leaf area, dry weight, the soluble sugar and peanut protein content. Nano-based kaolin clay layers were developed again by the same researcher in 2006 as a coating material to be used for controlled release of fertilizers. And, Corradini *et al*. (2010) studied chitosan nanoparticles as an antibacterial material for slow release of the fertilizers (Kashyap *et al*. 2015). The use of nanoporous zeolites was also studied both for increased efficiency and slow release of fertilizers (Chinnamuthu and Boopathi 2009). It was showed that SiO_2 nanoparticles improved germination in tomato (*Lycopersicum esculentum*) seeds (Manzer and Mohamed 2014, Ramalingam *et al.* 2015).

In a study conducted by Kottego *et al.* (2011), urea was modified with hydroxyapatite nanoparticles and encapsulated into *Gliricidia sepium's* wood spaces under pressure, and compared with commercial fertilizers. As a result of that study, it was reported that the nano-fertilizer showed an explosion first, followed by a slow release.

Lu *et al*. (2002) have studied the effect of TiO_2 nanoparticles on corn growth, and reported that TiO_2 has a significant effect on growth, and titanium nanoparticles enhance light absorption and photo-energy transfer. And, in another study they reported that SiO_2 and TiO_2 nanoparticles increase the nitrate reductase activity in soybean plants, and enhanced the plant absorption capacity.

2.1.2 Nano-pesticides

Pesticides are substances or mixtures of substances widely used to eliminate and control the harmful organisms, causing significant economic losses in agricultural production. The plant pests affecting the cultured products cause serious losses by limiting the product yield. Secondary metabolites (alkaloids, phenolics and terpenoids...) secreted by plant as self-preservation mechanism of nature provide defense and protective function against insect. In traditional pest control methods, producers excessively use pesticides, which pose significant economic burden (Sharon 2010). Although there are some benefits of pesticide use, it can cause major problems in terms of environment, animal and human health due to potential toxicity (chromosome abnormalities, inhibition of erythrocyte function, enzyme inhibition, water pollution, etc.).

Nanotechnology in new formulations to improve the effectiveness of these metabolites is made an important contribution. (Gogos *et al*. 2012, Scott and Chen 2012, Fraceto *et al*. 2014). Nanotechnological formulations can help to diminish out of favor toxic effects on non-target organisms, as well as develop physicochemical stability and prohibit degradation of the active agent by microorganisms (Gogos *et al.* 2012b, Durán and Marcato 2013, Perlatti *et al*. 2013). Furthermore, the release/carrier system can be customized to be diffusion controlled, erosion-controlled, swelling-controlled or combinations of these (Arifin *et al.* 2006, Tramon 2014, Fraceto *et al.* 2014), depending upon the mass-transfer system involved.

Nanotechnology allows companies to manipulate the properties of a carrier for controlled release of substances to be used as agricultural input through encapsulation or attaching to the nano material (adsorption, attachment, cross-linking, or chemical bonding etc.) (Jerobin *et al.* 2012, Nguyen *et al.* 2012). Therefore, many of the world's leading agricultural pharmaceutical companies take advantage of this technology and perform R&D work on the development of new nano-scale pesticide formulations (ETC Group 2004). And, the nano-encapsulation technique, which is one of the outcomes of these studies, is used to increase insecticidal effect of pesticides (Scrinis and Lyons 2007). In the nano-encapsulation technique, the nano-sized active pesticide compound is covered by a thin-walled shell as a protective layer. The main objective in the nano-encapsulation technique is the 'controlled release of the active compound', to increase the efficiency of the active substance and to reduce the amount of pesticide in order to protect the environment (Ali *et al.* 2014). These nano-formulations and potential applications were developed and patented by food and agriculture companies such as Monsanto, Syngenta and Kraft throughout the food chain (in pesticides, vaccines, veterinary medicine and nutritionally enriched foods) (ETC Group 2004).

Recently, there are reports present concerning use of chitosan nanoparticles as a delivery matrix for the release of pesticides in agriculture. Paula *et al.* (2011) prepared and characterized micro-spheres composed of chitosan and cashew tree gum, which were used as carriers of the essential oil of *Lippia sidoides*, which owns insecticidal characters. The results stated the relevance of chitosan for use as matrices to carry bioinsecticides designed to check the proliferation of insect larvae(Kashyap *et al.* 2015). Similarly, microcapsules of alginate and chitosan were prepared, characterized, and evaluated as a carrier system for imidacloprid (Guan *et al.* 2008). Imidacloprid was encapsulated with an efficiency of about 82%. In release assays, it was shown that the release time of the encapsulated insecticide was up to eight times longer, compared to the free insecticide, and that alterations in the concentrations of alginate and chitosan affected the release profile (Kashyap *et al.* 2015).

Nano-pesticides offer advantages to producers to achieve economic benefits. The longevity of biological activities of the nano-pesticides compared to other pesticides reduces the amount of pesticide to be used. Their high surface to volume ratio provide a better contact with the target organism and exhibit lethal effects in a shorter time. They eliminate the necessity of flammable solvents in the use of conventional pesticides, and increase safety of employees. In addition, reducing the loss of pesticides induced by environmental factors (vaporizing, sunlight) is possible with the use of nano-pesticides. Reduction of pesticide exposure of plant manufacturers, reduction of accumulation of pesticides in the environment are among the other advantages provided by nano-pesticides (ETC Group 2004, Peshin *et al.* 2009, Jo *et al.* 2009, Goswami *et al.* 2010, Teodoro *et al.* 2010).

Of the carrier systems, the halloysite nanotubes, which were developed as a pesticide carrier, can be given as an example study performed in this area. Halloysite nanotubes are generally defined as ultra-small hollow tubes, which are about 500 nm to 1.2 microns in length, and have a diameter less than 100 nm. Halloysite nanotubes are formed by utilizing the tensile caused by lattice mismatch between adjacent layers of silicon dioxide and aluminum oxide (Schaefer 2008, Du *et al.* 2010). The use of halloysite nanotubes have advantages such as reduction in the pesticide costs by effective use of small amount of pesticide inputs, an eco-friendly policy by having an active role in reducing pesticide residues accumulated in the environment, more efficient contact with the target product thanks to their nanoscale structures, and controlled release (Allen 1994, Ali *et al*. 2014). Liu *et al.* (2006) reported in their study that porous hollow silica nanoparticles stuffed with validamycin, which is a pesticide with widespread use, can be used effectively for controlled release of pesticides.

2.1.3 Nano-herbicides

Weeds cause significant economic losses in crop yields, posing a serious problem in agriculture. The chemicals used by producers for chemical weed control in the agriculture industry are called herbicides in general. However, despite the benefits of the herbicide use, there are very harmful consequences for humans, animals and the environment. The pesticide residues in the crops grown in soil contaminated with pesticides are accumulated in humans and animals fed with these products and lead to serious long-term problems. In addition, herbicides are mixed with groundwater and atmosphere because of seepage and evaporation, and cause harm to the environment, outside the areas of application.

It is possible to get rid of weeds by an environmentally friendly and low-cost approach thanks to the nano-herbicides, which is one of the products of the groundbreaking nanotechnology revolution all over the world (Pérez-de-Luque and Rubiales 2009). The amount of herbicides used will be lower when the active ingredient to be employed for controlling weeds is modified by a “smart” carrier system. Thanks to the high surface to volume ratio provided by the nanoscale dimensions, they will have a higher interaction with soil particles in the applied area. Although the conventional herbicides are effective on the weeds’ parts above-ground, they are not effective on the parts below ground (tubers etc.). In this case, the remaining parts of the plant below-ground become a source for the weeds in the next season. The specific receptors of weeds under the ground are targeted by modifying a herbicide molecule with encapsulated nanoparticles. In this way, less weeds will require a control in the next season.

Grillo *et al.* (2014) obtained chitosan/tripolyphosphate nanoparticles as carrier systems to paraquat herbicides. The data obtained showed that the nanoparticles were able to decrease the herbicide toxicity (Grilloa *et al.* 2014, Kashyap *et al.* 2015).

2.2 Use of nanobiosensors in agriculture

The agriculture industry cannot achieve the desired yield in products due to various environmental factors (the level of moisture, insects, plant viruses, weeds, temperature, etc.). It is inevitable to use technologies that will minimize yield loss in the agriculture industry, in order to meet the nutritional needs of an ever-growing world population. Nanosensors, which is one of the most comprehensive studies in nanotechnology, allow an effective evaluation by transferring nano-sized chemical, biological and electrical changes to the macro level.

Ambient conditions and product development such as the moisture level on the field, soil fertility, temperature, pests, weeds, plant diseases can be monitored simultaneously by using nanosensors. Transmission of these data simultaneously to a center offers many advantages to

Table 1 Summary of types nano-biosensors

Types of Nanobiosensors	Sample	Advantages	Reference
Mechanical Nanobiosensors	Nanocantilever	Highly mass sensitive, more the size decreases, more the mass reduces,	Ziegler 2004
Optical Nanobiosensors	Surface plasmon resonance	Enhanced sensitivity, remarkable optical properties	Haes and Duyne 2004
Nanowire Biosensors	Boron-doped silicon nanowires (SiNWs)	Extreme sensitivity, real time and quantitative fashion	Cui *et al.* 2001
Electronic Nanobiosensors	Lab on a chip	Independently addressed with capture probes for different target DNA molecules from the same or differ- ent organisms.	Jain 2005
Viral nanobiosensors	Herpes simplex virus (HSV)	Used a nanosensor for clinically relevant viruses	Perez *et al.* 2003
Probes Encapsulated by Biologically Localized Embedding (PEBBLE) nanobiosensors	Poly (decyl methacrylate)-Based Fluorescent PEBBLE	Capable of monitoring real-time inter- and intra-cellular imaging of ions and molecules, show great reversibility, stability to leaching	Cao *et al.* 2004
Nanoshell Biosensors	Gold nanoshells	Enhance chemical sensing by as much as 10 billion times	Hirsch *et al.* 2003
Enzyme-based nanosensors	4-Hydroxyphenylpyruvate Dioxygenase Enzyme	Promises reliable, precise, and low-cost techniques	Soto Garcia *et al.* 2015

producers as follows: The evaluation of nano-sized data in the ambient conditions allows effective use of agricultural inputs such as chemicals, nutrients and water (Rai *et al.* 2012). In addition, it is possible to be aware of the stress factors such as drought, crop pests, soil nutrient levels, presence of plant virus thanks to the nanosensors located on site. In light of these data, producers may minimize the product loss by intervening in no time (Farahi *et al.* 2012). Summary of types nano-biosensors is presented in Table 1.

The wireless nanosensor networks placed into the work area provide important data that pave the way for sensitive agricultural processes in order to maximize the output and yield, and to minimize agricultural inputs (Ingale and Chaudhari 2013). These data include water, fertilizer, pesticide, herbicide levels, suitable times for crop planting and harvesting, and information deemed necessary by producers, such as specific plant physiology, pathology and environmental conditions. Positive results will emerge such as economic gain, reduced environmental pollution and lower labor costs, thanks to decreased amount of inputs and central system for control mechanism through widespread use of nanosensors (Prasad *et al.* 2014).

There are numerous nano-based sensors such as metal nanoparticle-based sensors, Quantum Dot sensors, nanowire-based sensors, carbon nanotube-based sensors, mass-sensitive Nanosensors (nanocantilevers), Nanosensors based on metal oxide nano-structures.

The nanoparticle-based sensors are used for detecting pesticide residues in the agriculture industry. These sensors have superior properties compared with chromatographic techniques (Gas chromatography, HPLC) used for particle detection in the traditional methods since they are able to allow real-time, reliable, simple and low-cost detection on the work area (Liu *et al.* 2008, Kumaravel and Chandrasekaran 2011). Especially, metallic nanoparticles such as gold nanoparticles (AuNPs) and silver nanoparticles stand out thanks to their potential applications such as chemical and biological sensors (Lee *et al.* 2013). The protein coated nanocantilevers, which have a natural oscillating frequency, is a new class of ultra small silicon sensors used for the rapid detection of viruses, bacteria and other pathogens. When contaminants touch on the device, the small mass changes cause frequency shift in nanocantilever oscillations, and this can be detected quickly (El Amin 2006b).

Ahmed and Fekry (2013) prepared and develop a nanoparticle modified chitosan sensor for the assignment of heavy metals. The biosensor is based on the combination of chitosan cross-linked with glutaraldehyde modified with para-magnetic Fe_3O_4. The Fe_3O_4/CS nanocomposite film shows high accumulation capability for the determination and removal of heavy metals (arsenic, lead, and nickel) and ‘reports’ the process by an electrical reply (Kashyap *et al.* 2015).

Silicon-based nano-materials, especially the silicon nano-wires, has a great importance in the detection of pesticides. In a study conducted by Su *et al.* (2008), gold nanoparticles coated silicon nano-wires were studied and it was found that silicon nano-wire based electrochemical sensor is suitable for fast and precise pesticide detection at concentrations as low as 8 ng L^{-1}.

2.3 Utilization of nano-arrays in agriculture

Another application of nanotechnology in the agriculture industry is the reduction of the microarray analysis of plants down to the nanoscale. Microarray analysis allows mRNA analysis simultaneously for large number of genes (Aharoni and Vorst 2002). Plant physiological processes can be evaluated on the basis of DNA, through these analyses (Schena *et al.* 1998). In this case, changes in plant physiology are associated with changes in gene expression and the biological processes are studied in a more reliable manner. Microarrays are used for characterizing genes involved in the regulation of biological characteristics (circadian rhythm, plant defense mechanisms, oxidative stress responses, phytochrome signaling, fruit ripening, seed development and nitrate assimilation, etc.) of products grown in the agriculture industry for a long time (Aharoni and Vorst 2002, Kumari and Yadav 2014).

Reduction of microarrays down to nanoscale in the light of the nanotechnological developments is highly advantageous since it reduces the required sample volume and the amount of analyte. In addition, nanotechnology can be used to increase the efficiency of the microarrays, through the development of signaling and mobilization strategies of microarrays. There are studies that use organic-dye added silica nanoparticles in DNA detection. It is possible to encapsulate floropores into a single nanoparticle. In this way, a stimulation at the nanoscale can generate a strong fluorescence signal. As a result of this study, obtained signal becomes quite large when the probe used is marked with DNA-dye added silica nanoparticles. Using this strategy, the target DNA molecules can be fixed at concentrations as low as 8×10^{-13} M (Zhao *et al.* 2003, Yan *et al.* 2007, Kumari and Yadav 2014).

Quantum dots (QD) are nanoscale semiconductor nanocrystals. QD photoluminescence is used for bio-imaging and biological labeling (Gao *et al.* 2001, 2004). There are studies to determine DNA sequences using QD. A quantumdot is a semiconductor particle that can be used as a fluorophore (e.g., ZnS, CdSe, CdS) (Bruchez *et al.* 1998, Medintz *et al*. 2005, Somers *et al.* 2007). QDs, i.e., semiconductor nanocrystal fluorophores, are used for immuno-labeling in plant chromosomes, particularly (Muller *et al.* 2006, Kumari and Yadav 2014). However, there is a point to be considered in the use of QD; the semiconductor material used in QD is toxic to humans. Therefore, non-toxic polymer encapsulated QDs are come to the fore for an *in vivo* use

(Medintz *et al.* 2001, Bakalova *et al.* 2004).

The multi-adenine DNA chains processed on an area of 4mm silicon substrate at 50 nm resolution using soft-lithography were hybridized with multi-thymine DNA at 20 nm. Entire hybridization was performed by only three fabrication processing steps. In addition, a main silicone mold that can be used repeatedly was sufficient (Noh *et al.* 2008, Kumari and Yadav 2014).

2.4 Nanotechnology in irrigation water filtration

The depletion of the available water resources in line with an increasing population directs researchers to study the usability of emerging technologies in this area. In the agriculture industry, which is among the areas that consume water resources mostly, the quality of water to be used directly affects the crop to be produced. Therefore, effective treatment of the existing water resources for reuse, improving the quality of water used in agriculture, reducing the costs of studies conducted in this field are among the important research areas.

The major disadvantage of water treatment methods is the higher costs, and it is possible to reduce these costs, thanks to nanotechnology. Nanotechnological applications provide many advantages in water treatment. The large surface to volume ratio makes some nanoparticles capable of having minimal pressure relief potential for a magnetic separation. Hypercatalyst dechlorinates (chlorine remover), which is one of the nanotechnology products, is about 1000 times faster compared with any commercial catalysts. The membranes, which include nano-sized materials, increase resistance to pollution. Nano-sized materials make the surfaces long-term durable against biopollution and biocorrosion (Cui *et al.* 2010).

The water treatment techniques that feature nanotechnology include membranes and filters based on carbon nanotubes, nanoporous ceramics and magnetic nanoparticles in particular (Hillie and Hlophe 2007). The filters made of carbon nanotubes, which have a semiconductor and metallic characteristic depending on their geometries, can be used to remove nano-sized toxic substances and contaminants in water to be treated. The cylindrical structure is maintained in filters made of carbon nanotubes completely. In this way, the filters become durable in long-term use and can be cleaned easily. Therefore, the carbon nanotubes stand out with their capability to remove pathogens, lead, uranium, heavy metals such as arsenic in water treatment (Prasad *et al.* 2014).

Nanoceramics filters utilize the fact that the opposite charges attract each other. The positively charged nanoceramic filters easily remove the negatively charged viruses and bacteria in the water to be treated. This filter system separates microbial endotoxins, genetic materials, pathogenic viruses and micro-scale particles (Argonide 2005). Water sources may also contain organic particles, pesticides, and herbicides. Researchers highlight the use of nanoparticle-filters in their studies to remove the organic particles, herbicides, and pesticides accumulated in the water (Karn *et al.* 2009). Nano-scale zero valent iron is the most widely used nanomaterial for water treatment in the soil and groundwater (Gilman 2006).

Macro characteristics of the particles (electrical charge, solubility, reactivity, etc.) differ in the nano-scale. Consequently, many ideas that were imaginary once now become a reality by utilizing the properties of these nano-sized particles. Thanks to magnetic nanoparticles, it is possible to separate the toxic substances present in water, even at very low magnetic field gradients. For example, nano-crystals, such as mono-dispersive magnetite (Fe_3O_4), can be used for the removal of arsenic through a strong irreversible interaction with arsenic, while maintaining their magnetic properties (Yavuz *et al.* 2006).

2.5 Using nanotechnology to improve crop yield

The minimum input and maximum output yield approach in the agriculture industry causes adoption of the technologies that could lead to an increase in crop yield and quality as quickly as possible. Thanks to nanotechnology, it is possible to achieve a desired increase in the crop production and quality through proper amount of inputs at the right time in agricultural products. Researches related to this area are increasing gradually. Recently, literature has reported the positive effects of NPs on plants (Zezzi Arruda *et al.* 2015, Ditta and Arshad 2015). Existing studies in the literature for improving product with nanoparticles are presented in Table 2.

Table 2 Some of existing studies in the literature for improving product with nanoparticles

Used NPs	Target plants	Method of Application	Results	Reference
TiO_2	Spinach	Administered to the seeds or sprayed onto the leaves	Enhancement of plant growth, increase the activity of several enzymes, promote the adsorption of nitrate	Zheng *et al.* 2005
nano-anatase	Parsley	Administered to the seeds	Increases in the percentage of germination ,the germination rate index, the root and shoot length, the fresh weight, the vigor index, and the chlorophyll content of the seedlings	Dehkourdi *et al.* 2013
Biogenic nanoparticles derived from leaves of *Tridax procumbens*	Wheat grains	Administered to the seeds	Increase the seedling vigor and to improve the germination percentage and the seedling growth of Tridax procumbens L. and triggering the antioxidative mechanism in germinating seeds under chilling	Bhati-Kushwaha *et al.* 2013
Graphene quantum dots	*Allium sativum Coriandrum sativam L*	Seeds were treated with 0.2 mg mL^{-1} of graphene quantum dots for 3 h before planting	Enhanced the growth rate both two plants	Late *et al.* 2015
TiO_2	*Salvia*	Seeds were exposed to 60 mgL^{-1} of bulk and nano sized TiO_2 after 21days of seed incubation.	Improved germination rate of Salvia	Feizi *et al.* 2013
Alumina	*Lemna minor*	Administered to the seeds	Enhance the growth of *L. minör,* the enhancement of the biomass accumulation	Juhel *et al.* 2011
ZnO	*Prosopis juliflora-velutina*	Administered to the plant root, leaf, seed for 15 days	Increases in the specific activity of CAT (in the root, steam and leaves) and APX (only in the leaves)	Hernandez-Viezcas *et al.* 2011

Table 2 Continued

TiO_2	*Mentha Piperita*	Seeds were treated with NP-TiO_2	Root length was significantly influenced by 100mg L^{-1} concentration of NP-TiO_2	Samadi *et al.* 2014
ZnO	Peanut	Treatment of nanoscale ZnO (25 nm mean particle size) at 1000 ppm concentration promoted both seed germination and seedling vigor	Increasing stem and root growth and pod yield per plant was 34% higher compared to chelated bulk $ZnSO_4$	Prasad *et al.* 2012
TiO_2	*Salvia officinalis*	Treatment of various concentrations of TiO_2 particles, 0, 10, 50, 100, 200 and 1000 mg l^{-1} on plant extract	The highest value of *Cis*-Thujene (34.5 %) and 1,8-Cineol (21.2 %) were achieved with 200 mg l^{-1} nano-TiO_2, the highest root and shoot tissues were obtained from plants exposed to 100 mg l^{-1} TiO_2	Ghorbanpour 2015
Silver	*Ocimum bacilicum L.*	Sprayed on basil plant at seed growth stage.	Improvement in the seed yield	Nejatzadeh-Barandozi *et al.* 2014
ZnO	*Oryza sativa L.*	Treated different levels of zinc oxide nanorods (0, 250, 500 and 750 mg L^{-1})	Significantly increased in seed priming with 30% Polyethylene glycol under nano-ZnO stress	Hu *et al.* 2015

In a study, Sedghi *et al.* (2010) studied the effect of nano-iron oxide on soybean yield and quality. They have applied nano iron oxide at 5 levels (0, 0.25, 0.5, 0.75 and 1 g L^{-1}). As a result of their study, they have stated that nano-iron oxide at 0.75 gL^{-1} concentration increase the pod dry weight and leaf + pod dry weight, and the highest grain yield was 48% higher compared with the control, achieved by 0.5 gL^{-1} nano-iron oxide.

Development of the agricultural products takes time depending on the crop grown. Therefore, producers prefer methods that trigger germination earlier, in order to obtain crops in a shorter time. One outcome of this quest is the use of carbon nanotubes for this purpose. In studies, it was found that the carbon nanotubes used in lower doses are able to penetrate thicker seed layers more easily, stimulate germination and activate the enhanced growth of tomato plants (Khodakovskaya *et al.* 2009). Carbon nanotubes are used as nano-carriers as well. Carbon nanotubes served as nano-carriers in DNA transfer into tobacco cells (Liu *et al.* 2009a, b). Carbon nanotubes are widely utilized in the agriculture industry from applications to improve plant disease resistance, feed utilization and agrochemical applications for enhanced plant growth to genetic transformations (Liu *et al.* 2010, Nair *et al.* 2010). McLamore *et al.* (2010) have studied regulation of plant hormone like auxin which is responsible for proper root growth and seedling organization.

In a study conducted by Han *et al.* (2012), potential effects of oxidized multi-walled carbon nanotubes (o-MWCNTs) at lengths ranging from 50 and 630 nm in the wheat plant physiology and development were evaluated by investigating seed germination, root growth, stem length and effects on plant biomass. As a result of the study, it has been reported that faster root growth and more plant biomass were observed in the plants compared to the control samples, after exposure to o-MWCNT medium for 7 days. The cell length of the root region was increased up to 1.4 times for the germinated and grown seedlings in the o-MWCNT medium (80 mg/mL), and also for the o-MWCNT applied wheat seedlings there was a significant increase in the dehydrogenase activity associated with the concentration. These findings suggest that o-MWCNT may promote cell elongation in the root system significantly, and increase the dehydrogenase activity resulting in faster root growth and higher biomass production.

3. Conclusions

Advantageus solutions is achived to many problems in the agricultural sector thanks to the potential applications of nanotechnology. The effective use of agricultural inputs leads to economic benefits and environmentally friendly policies, through the minimum input - maximum efficiency approach. The 'precision agriculture' created by the use of nanotechnological applications (smart distribution systems, nanosensors, nanoarrays, nanofilters and nanoparticles, etc.) effectively and correctly in the agriculture industry provide benefits such as protection of plants, monitoring plant growth, detection of plant and animal diseases, increasing global food production, water treatment, food quality improvement and waste reduction for sustainable agriculture, etc. However, it would be quite wrong to limit the use of nano-products with the applications given above in the agriculture industry. It is not too far away for the agriculture industry to have previously unimagined range of applications based on nanotechnological studies.

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