Nanoparticles, Soils, Plants and Sustainable Agriculture

Chapter · October 2016

DOI: 10.1007/978-3-319-39303-2_10

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Chapter 10
Nanoparticles, Soils, Plants and Sustainable Agriculture

Tarek A. Shalaby, Yousry Bayoumi, Neama Abdalla, Hussein Taha, Tarek Alshaal, Said Shehata, Megahed Amer, Éva Domokos-Szabolcsy, and Hassan El-Ramady

Abstract Humanity faces major challenges involving energy, water, food, environment, poverty, diseases, education, democracy and population. Green nanotechnology could be a solution for providing sustainable energy, clean water and a better environment. Various nanomaterials can sustain the agricultural sectors. Here we review the applications of nanoparticles for soil security and plant nutrition.

Keywords Nanoparicles • Terrestrial environments • Sustainable agriculture • Soil security • Plant nutrition

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S. Ranjan et al. (eds.), *Nanoscience in Food and Agriculture 1*,
Sustainable Agriculture Reviews 20, DOI 10.1007/978-3-319-39303-2_10

10.1 Introduction

Green nanotechnology is the nascent area of research involving the design of nanoscale substances, materials, and processes through green chemistry and green engineering that results in the development of new performance without adverse consequences to humans and the biosphere (McKenzie and Hutchison 2004). It has been said that green nanotechnology in its simplest form is preserving the applications while minimizing or eliminating the negative implications of nanomaterials (Eckelman et al. 2008). It could be noted that this kind of nanotechnology is (1) environmentally benign and sustainable, (2) is intended to contribute to the solution of some environmental problem or (3) at a minimum it should perform better than alternative non-green nanotechnologies (Geoffrey and Granqvist 2011). Recently, several publications focused on the field of green nanotechnology (e.g., McKenzie and Hutchison 2004; Eckelman et al. 2008; Dhingra et al. 2010; Geoffrey and Granqvist 2011; Guo 2012; Virkutyte and Varma 2013; Rickerby and Morrison 2014; Basiuk and Basiuk 2015).

Literally nanotechnology means any technology on a nanoscale that has applications in the real world (Bhushan 2010). The term "nanotechnology" was invented by Professor Norio Taniguchi at the University of Tokyo in 1974 with the following definition: *Nano-technology is the production technology to get the extra high accuracy and ultra fine dimensions*, i.e. *the preciseness and fineness on the order of* 1 nm (*nanometer*), 10^{-9} *m in length.* According to NASA's definition, "*nanotechnology is the creation of functional materials, devices and systems through control of matter on the nanometer length scale* (1–100 *nanometers*), *and exploitation of novel phenomena and properties* (*physical, chemical, biological, mechanical, electrical…*) *at that length scale*" (Meyyappan 2004). It could be defined nanotechnology as a promising field of interdisciplinary research. It can open up a wide array of opportunities in various fields like agriculture, pharmaceuticals, medicine and electronics. Therefore, the potential benefits and uses of nanotechnology are enormous. Concerning the application of nanotechnology to agriculture is also getting attention nowadays (Prasad et al. 2014; Shapira and Youtie 2015; Resham et al. 2015; Nath 2015). It has been widely recognized that, reducing the impact of industry on the environment as an important priority for achieving sustainability. As a consequence, products and production methods are being modified, supply chains are evolving and increased attention is paid to the disposal of waste and recycling. Therefore, nanotechnology can play a key role in these developments because it has the potential to confer substantial societal, economic, and environmental benefits through more efficient energy generation and storage systems, reduction of emis-

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sions, resource saving, and substitution of hazardous substances (Rickerby and Morrison 2007; Rickerby and Morrison 2014). In developing countries, a large proportion of people face daily food shortages as a result of environmental impacts or political instability, whereas in the developed world there is surplus of food. The drive for developing countries is to develop drought and pest resistant crops, which also maximize yield. The potential of nanotechnology to revolutionize textile, materials, information and communication technology, the health care and energy sectors has been well publicized (Prasad et al. 2014).

Therefore, the role of nanoparticles in enhancing soil security, different effects on plants as well as the significance of these nanoparticles for plant nutrition and hence sustainable agriculture will be highlighted.

10.2 Nanoparticles for Sustainable Agriculture

Humankind faces a lot of challenges. These challenges can be listed according to Nobel Laureate Richard E. Smalley (1996) including the following top ten problems: (1) energy, (2) water, (3) food, (4) environment, (5) poverty, (6) terrorism and war, (7) disease, (8) education, (9) democracy, and (10) population. Furthermore, it could be used this list according to the green nanotechnology for providing energy, clean water and a good environment in a sustainable way (Geoffrey and Granqvist 2011). It could be noticed that, about 50 % from these previous challenges in close relation with the agriculture.

Starting with agriculture, it is the basic activity by which humans live and survive on the Earth (Reddy 2015). This activity has a lot of systems including conventional, conservation or sustainable and organic agricultural systems. Concerning conventional agriculture, it has largely been characterized by tillage, which leaves soil vulnerable to erosion. It could be also characterized by minimal soil disturbance, diversified crop rotations, and surface crop residue retention to reduce soil and environmental degradation while sustaining crop production. These both tillage and crop residue burning as conventional farming practices have substantially degraded the soil resource base, with a concomitant reduction in crop production capacity. Due to the conventional farming practices, continued loss of soil is expected to become critical for global agricultural production. This conventional mode of agriculture through intensive agricultural practices achieves production goals, but simultaneously degrades the natural resources (Farooq and Siddique 2015).

On the other hand, conservation agriculture is a new paradigm for achieving sustained agricultural production and is a major step in the transition to sustainable agriculture. Conservation agriculture is widely recognized as a viable approach to creating a sustainable agriculture (Farooq and Siddique 2015). It is a resource-saving agricultural production system that aims to achieve production intensification and high yields while enhancing the natural resource base through compliance with four interrelated principles viz. minimal soil disturbance, permanent residue cover, planned crop rotations and integrated weed management, along with other good production practices of plant nutrition and pest management. Conservation agriculture is a set of technologies, including minimum soil disturbance, permanent

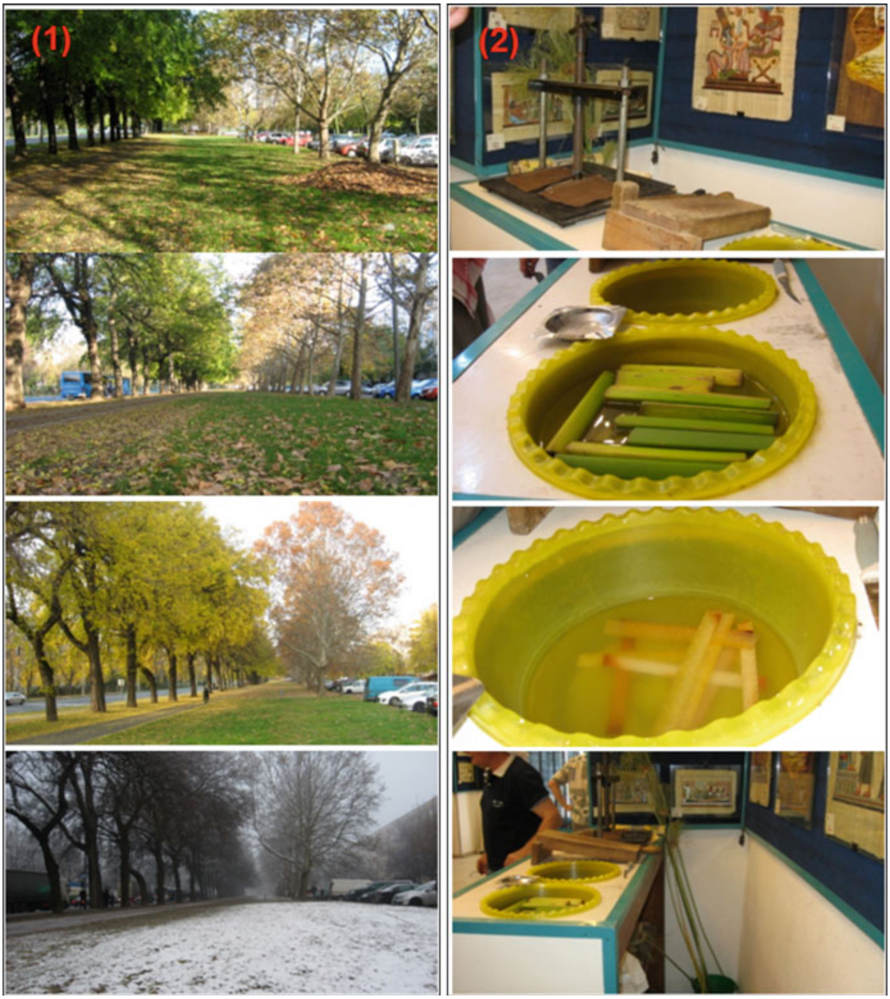

Fig. 10.1 Plants can sustain our life: composting from leaves (from September till snowing by February in Böszörményi Street, Debrecen, Hungary; photo 1), whereas photo 2 represents some steps explaining how the ancient Egyptian used the papyrus plant (*Cyperus papyrus*) for making papyrus paper (Photos by El-Ramady)

soil cover, diversified crop rotations, and integrated weed management (Friedrich et al. 2012), aimed at reducing and/or reverting many negative effects of conventional farming practices such as soil erosion, soil organic matter decline, water loss, soil physical degradation, and fuel use (FAO 2008; Farooq and Siddique 2015).

Therefore, the growing concerns for sustainable agriculture are in response to the limitations of both low-input, traditional agriculture and intensive modern agriculture relying on high levels of inputs for crop production (Figs. 10.1 and 10.2). Sustainable agriculture relies on practices that help to maintain ecological equilibrium and encourage natural regenerative processes such as nitrogen fixation, nutrient cycling, soil regeneration, and the protection of natural enemies of pest and

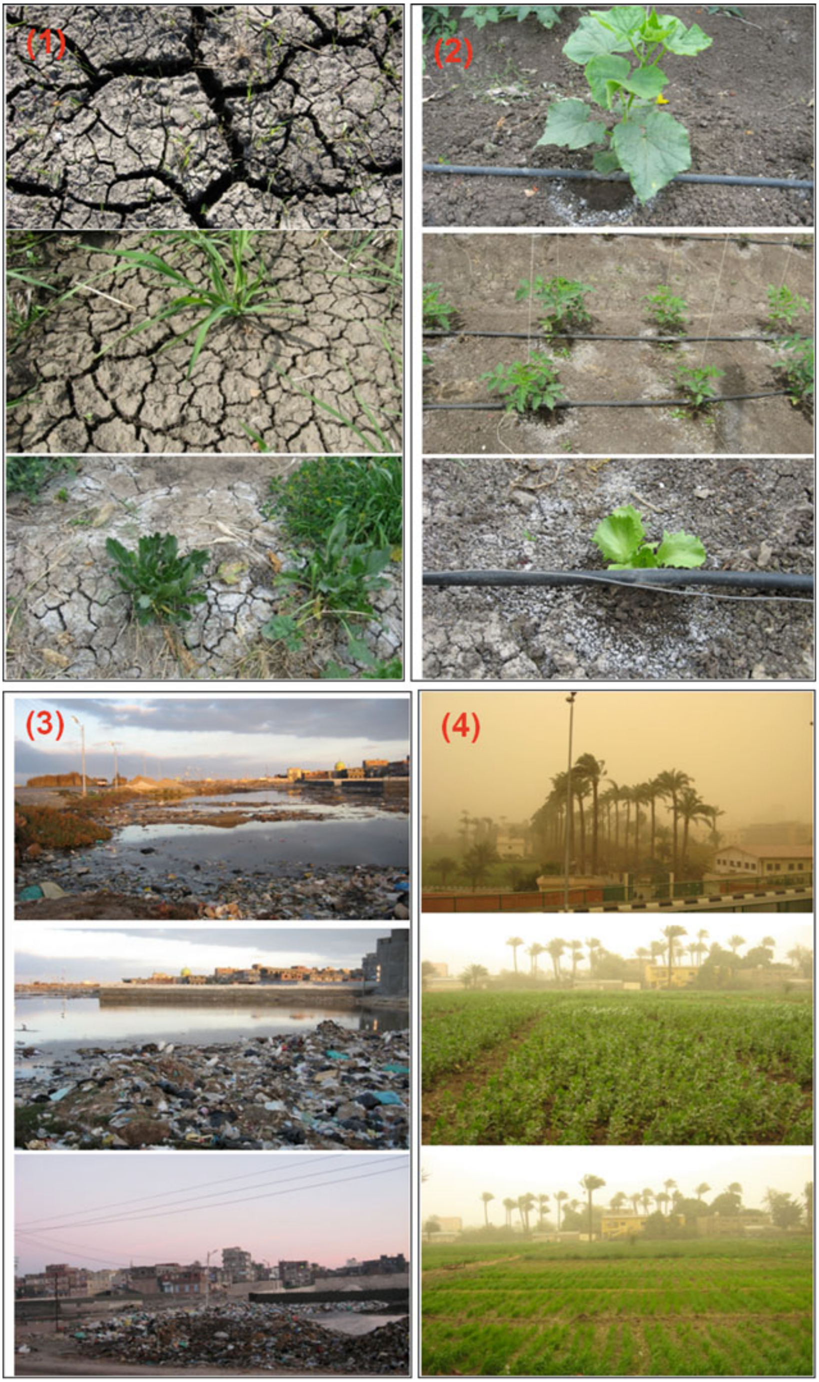

Fig. 10.2 Soils suffer from salinity and/or alkalinity (salt-affected soils) in field (photo 1) or in green house under drip irrigation (photo 2), pollution and water logging in Kafr El-Sheikh (photo 3) and sandy storm on February 11, 2015 (photo 4) in Giza (Photos by El-Ramady)

diseases as well as the targeted use of inputs. Agricultural systems relying on such approaches not only support high productivity, but also preserve biodiversity and safeguard the environment (Farooq and Siddique 2015).

Concerning nanoparticles and its behavior in frame of sustainable agriculture, it is an emerging issue all over the world. Whereas, there are several publications including book chapters, reviews, books such as Anandaraj et al. (2011), Chen and Yada (2011), Ditta (2012), Prasad et al. (2012, 2014), Tarafdar et al. (2013), Thul et al. (2013), El Beyrouthya and El Azzi (2014), Takeuchi et al. (2014), Mukhopadhyay (2014), Ngô and Van de Voorde (2014), de Oliveira et al. (2014), Wigger et al. (2015), Ditta et al. (2015), Thul and Sarangi (2015), Patil et al. (2016), Salamanca-Buentello and Daar (2016), Hasegawa et al. (2016), and Lourtioz et al. (2016). It is worth to mention that, recently the American Chemical Society published some publications concerning this subject e.g., Shamim and Sharma (2013), Doong et al. (2013), Park and Appell (2013), and Hu et al. (2014a).

Regarding to soil, it is biogeochemically dynamic entities that play an important role in sustaining life forms within the Earth's critical zone by regulating processes in terrestrial ecosystems. Furthermore, soils can provide critical support essential for life on the earth, regulate processes across diverse terrestrial ecosystems, and interact with the atmosphere (Adewopo et al. 2014). Concerning the most important and emerging research area in soil sciences, it is well established some thematic areas for this subject including soils as a key regulator of ecosystem functions, role of soils in public health and human well-being, soils mediating nutrient cycling, transport processes, and plant-soil – microbial interactions, soil formation and degradation and soil information systems (Figs. 10.1 and 10.2). Therefore, identifying priority research challenges within a scientific area is a daunting task, but the outcomes could present unparalleled opportunities for advancing the science. However, the uniqueness of soil science lies in its rich blend of biology, chemistry, pedology, physics, mathematics, and social sciences as well as communication (Adewopo et al. 2014).

Therefore, it could be concluded that, nanoparticles or nanomaterials can be used in sustaining the agricultural sectors including food, energy, water, and soils, within food security, energy security, water security and soil security. We should broaden our view on nanoparticles or nanomaterials considering different potentials for a sustainable materials management.

10.3 Enhancing Soil Security

Soil security has been defined in analogy with food security, which aims at the long term sustainable production of sufficient quantities of food, providing a permanent feeling of security to world citizens. This implies, however, much more than striving for a higher production as such, as many socioeconomic, institutional, and ethical aspects also play a key role (Bouma et al. 2015). The security concept is more complicated when applied to soils. Rather than relate to a sustainable, daily need in terms of food intake, soil security relates to what might happen if soils degrade to the extent that sufficient food production is not feasible anymore. Soil degradation is a long-term process, very much related to varying socioeconomic conditions. Except for erosion, its effects are often gradual and difficult to communicate and translate into environmental and economic values. However, when soils degrade to the extent that they cannot anymore provide certain ecosystem services, of which food production is only one provisioning service, the consequences for society are devastating. To mitigate degraded soils is very difficult and even impossible when soil has been removed by erosion. The challenge, therefore, is to create early awareness about the dangers of soil degradation that may, in the end, terminate many ecosystem services the soil can provide (Bouma et al. 2015).

A side from soil security, food security was and will remain a major among global issues of the twenty-first century. Furthermore, principal determinants of food security include the availability and quality of soil resources, and their interactions with water resources as well as vegetation (crop species) through energy-based inputs using managerial skills for optimizing the net primary productivity (Lal 2015). This net primary productivity is specifically affected by critical linkages that govern some specific functions of nexuses. These nexuses include the first one, soil and water for the plant, available water capacity by influencing water retention and transmission, conversion of blue and grey into green water, and moderating the effects of pedologic and agronomic droughts (Lal 2015). The second includes soil and vegetation for biogeochemical cycling, which determines elemental budgets (i.e., C, N, P, and S), nutrient use efficiency, root distribution and turnover and soil/root respiration. Whereas, the third is vegetation and energy for energy/mass transformation and influencing energy productivity, ecosystem C budget, and biomass feedstocks for biofuel production. Finally, the fourth one is energy and water affecting the hydrological cycle with specific impacts on water and energy balance on a landscape, energy use in irrigated systems, and moderation of the hydrological/meteorological droughts. These nexuses affect and are affected by climate changes and variability on the one hand and anthropogenic perturbations (human demands) on the other (Lal 2015).

Lal (2015) reported about the importance of nexuses and their inter-connectivity. He mentioned that, there is a close relationship between soil security, water security, climate security, energy security, economic security and political security. Concerning the food security, it includes availability, access, nutritional quality, and retention, which strongly depends on soil security (quality, resilience), water security (quality, renewability, availability), energy security (dependability, supply, price), climate security (optimal temperature and moisture regimes, and low frequency of extreme events), economic security (income and access to resources), and political stability (peace and harmony). Therefore, the co-productivity generated by the anthropogenic use of primary resources (soil, water, climate) and secondary inputs (amendments, fertilizers, irrigation, tillage) must be optimized. Understanding and judiciously managing the water-soil-waste nexus for food security is important to enhancing human wellbeing, achieving the sustainable use of natural resources, improving the environment and sustaining ecosystem functions and services (Lal 2015).

10.4 Nanoparticles and Plants

Nanotechnology is a new emerging and fascinating field of science. Nanotechnology permits advanced research in many areas and nanotechnological discoveries could open up novel applications in the field of biotechnology and agriculture (Siddiqui et al. 2015a). Nanomaterials, as a term is based on the prefix “nano,” which originates from the Greek word meaning “dwarf.” More precisely, the word nano means 10^{-9} or one billionth of a meter (Huang et al. 2015). The word nanomaterial is generally used for materials with a size ranging between 1 and 100 nm (Rai and Ingle 2012). Generally, nanomaterials refer to a colloidal particulate system, in which size ranging from 10 to 1000 nm, possessing unique properties, such as size dependent qualities, high surface-to-volume ratio, and promising optical properties (Aslani et al. 2014). It could be also defined nanoparticles, which refer to a category of nanomaterials, a submicron or even ultramicron size particles obtainable as high performance radiant resistant materials, magnetic materials, solar battery materials, packaging materials, and magnetic fluid materials (Aslani et al. 2014). Furthermore, it could be divided nanoparticles into natural and anthropogenic (manufactured or engineered) particles. Depending on their chemical composition, these particles can be further separated into carbon-containing and inorganic nanoparticles. Hence, the C-containing or inorganic nanoparticles can be formed using biogenic, geogenic, atmospheric and pyrogenic processes (Nowack and Bucheli 2007).

Due to their great surface area per mass unit, nanoparticles are expected to be more biologically active than larger sized particles of the same chemical composition (Sozer and Kokini 2009). Beside a very large specific surface area, nanoparticles high unique properties including surface energy, and quantum confinement (Ma et al. 2010). These unusual properties may result in substantially different environmental fate and behaviors than their bulk counterparts. Hence, an emerging area of research nowadays is focused on short and medium term studies of the environmental and ecological impact of released nanoparticles. Due to the interaction between nanoparticles and plants, many morphological and physiological can be changed, depending on the properties of these nanoparticles (Siddiqui et al. 2015b). Furthermore, efficacy of these nanoparticles is determined by their chemical composition, size, shape, surface covering, reactivity, and most importantly the dose at which they are effective in the terrestrial environments (Khodakovskaya et al. 2012; Dasgupta et al. 2015, 2016a, b, c; Ranjan et al. 2014, 2015, 2016; Jain et al. 2016; Maddineni et al. 2015).

Several positive and negative effects of nanoparticles on plant growth and development have been already reviewed by many researchers from their findings (e.g., Nowack and Bucheli 2007; Ju-Nam and Lead 2008; Handy et al. 2008; Mueller and Nowack 2008; Stampoulis et al. 2009; Ruffini and Cremonini 2009; Kahru and Dubourguier 2010; Ma et al. 2010; Nair et al. 2010; Peralta-Videa et al. 2011; Menard et al. 2011; Khot et al. 2012; Pan and Xing 2012; Smita et al. 2012; Ma et al. 2013; Gardea-Torresdey et al. 2014; Deng et al. 2014; Aslani et al. 2014; Hudson and Roberta 2015; Huang et al. 2015; Siddiqui et al. 2015b; Chichiriccò and Poma 2015; Aliofkhazraei 2016; Abd-Alla et al. 2016; Gil-Díaz et al. 2016; Le Van et al. 2016; Wen et al. 2016). They found that, the impact of engineered nanoparticles on plants depends on the composition, concentration, size and physical and chemical properties of engineered nanoparticles as well as plant species. Efficacy of these engineered nanoparticles depends on their concentration and varies from plant to plant. However, this review covers plausible role nanoparticles in seed germination, plant growth (shoot and root biomass) and photosynthesis.

A recent trend in nanotechnology has been known as nano-bio interactions to investigate the interactions of nanomaterials with biological systems like plants

(Albanese et al. 2012). Plant growth and development starts from the germination of seeds followed by root elongation and shoot emergence as the earliest signs of growth and development. Therefore, it is important to understand the plant growth and development in relation to nanoparticles. The reported data from various studies suggested that effect of nanoparticles on seed germination dependent on their concentrations. There are several authors studied the effects of nanoparticles on plants including many metals/metaloids or metal oxide such as:

1. Cerium (Zhao et al. 2013b, 2014; Rico et al. 2015; Hong et al. 2014),
2. Copper (Shaw and Hossain 2013; Ouda 2014; Lalau et al. 2014; Nair and Chung 2014; Perreault et al. 2014; Shi et al. 2014; Da Costa and Sharma 2015),
3. Gold (Zhai et al. 2014; Gunjan et al. 2014; Dan et al. 2015),
4. Iron (Ghafariyan et al. 2013; Faria et al. 2014; Pardha-Saradhi et al. 2014; Burke et al. 2015; Libralato et al. 2016),
5. Nickel (Faisal et al. 2013; Oukarroum et al. 2015),
6. Selenium (Domokos-Szabolcsy et al. 2012; Husen and Siddiqi 2014; El-Ramady et al. 2015a, b, c, 2016),
7. Silicon (Li et al. 2012; Suriyaprabha et al. 2012a, b; Hussain et al. 2013; Siddiqui et al. 2014; Siddiqui and Al-Whaibi 2014; Kalteh et al. 2014; Roohizadeh et al. 2015; Wang et al. 2015b),
8. Silver (Kaveh et al. 2013; Silva et al. 2014; Larue et al. 2014a, b; Boenigk et al. 2014; Geisler-Lee et al. 2014; Ouda 2014; Meena and Chouhan 2015; Razzaq et al. 2016),
9. Titanium (Foltete et al. 2011; Gao et al. 2013; Burke et al. 2015), and
10. Zinc (Prasad et al. 2012; Pokhrel and Dubey 2013; Hu et al. 2014b; Zhao et al. 2013a, 2014; Tyagi et al. 2014; Bandyopadhyay et al. 2015; Vochita et al. 2016),

It could be listed some toxic and beneficial effects of both nano-SiO_2 and nano-ZnO in the following Tables (Tables 10.1 and 10.2). Concerning these effects, it could be concluded some findings as follows:

Table 10.1 Beneficiary concentration(s) of zinc and silicon nanoparticles for plants (Siddiqui et al. 2015b) comparing with nano-Se

Nanoparticle (plant species)	Beneficiary concentration	Part of plant/process	Reference(s)
Nano-ZnO (*Cucumis sativus*) fruit	400 mg kg^{-1}	Micronutrients: Cu, Mn and Zn	Zhao et al. (2014)
Nano-ZnO (*Cicer arietinum* L.)	1.5 mg kg^{-1} (foliar spray)	Shoot dry weight	Burman et al. (2013)
Nano-ZnO (*Vigna radiate*)	20 mg kg^{-1} (foliar spray, suspension)	Biomass	Dhoke et al. (2013)
Nano-SiO_2 (*Zea mays* L.)	15 kg ha^{-1}	Growth parameters	Yuvakkumar et al. (2011) and Suriyaprabha et al. (2012a)
Nano-Se (*Nicotinia tabacum* L.)	100 mg kg^{-1}	Callus initiation and microshoot formation	Domokos-Szabolcsy et al. (2012)
Nano-Se (*Arundo donax* L.)	100 mg kg^{-1}	Rooting and other growth parameters	Domokos-Szabolcsy et al. (2014)
Nano-Se (*Triticum aestivum* L.; *Raphanus sativus* L.)	100 mg kg^{-1}	Production of biofortified sprouts using micro-farm system	El-Ramady et al. (2016)

Table 10.2 Effect of nano-ZnO and nano-SiO_2 on germination and growth of some plants or microbes

Nano-particle	Crop/plant/microorganism	Comments (toxicity or enhancement according to nanoparticles concentration)	References
Nano-ZnO	Peanut (*Arachis hypogaea*)	Improved growth and yield (up to 1000 mg kg^{-1})	Prasad et al. (2012)
	Cluster bean (*Cyamopsis tetragonoloba* L.)	Improved shoot-root growth, chlorophyll (photosynthetic pigment), total soluble leaf protein content, rhizospheric microbial population, and P nutrient-mobilizing enzymes including phytase, acid and alkaline phosphatase (foliar up 10 mg kg^{-1})	Raliya and Tarafdar (2013)
	Ryegrass (*Lolium perenne*)	Reduced biomass, shrank root tips, epidermis and root cap broken, highly vacuolated and collapsed cortical cells (up to 1000 mg kg^{-1} in Hoagland solution)	Lin and Xing (2008)
	Cabbage (*Brassica oleracea* var. capitata L.)	Dose-dependent inhibition of germination in aqueous suspension (1000 mg kg^{-1})	Pokhrel and Dubey (2013)
	Bacteria (*Bacillus subtilis*) (*Escherichia coli*)	Mild toxicity due to reactive oxygen species (ROS) production (up to 5000 mg L^{-1})	Adams et al. (2006)
	Bacteria (*Pseudomonas putida*)	Inhibition of bacterial growth (up to 100 mg L^{-1})	Li et al. (2011)
	Bacteria (Rhizobiales, Bradyrhizobiaceae, Bradyrhizobium)	Decline in bacterial communities and reduced diversity (500 mg kg^{-1} soil for nano-ZnO)	Ge et al. (2012)
Nano-SiO_2	Maize (*Zea mays* L.)	Enhanced plant dry weight and levels of organic compounds such as proteins, chlorophyll and phenols (up to 15 kg ha^{-1})	Suriyaprabha et al. (2012a, b)
	Tomato (*Lycopersicum esculentum* Mill)	Improved seed germination (up to 8 g L^{-1})	Siddiqui and Al-Whaibi (2014)
	Mouse-ear cress (*Arabidopsis thaliana*)	Increased root length at 400 mg L^{-1}, but reduced root length at 2000 and 4000 mg L^{-1}	Lee et al. (2010)
	Lupin (*Lupinus sp.*) and wheat (*Triticum spp.*)	No signs of toxicity were observed and did not affect seed germination and did not show phytotoxicity (2000 mg L^{-1})	Hussain et al. (2013)
	Bacteria (*Bacillus subtilis*) (*Escherichia coli*)	Mild toxicity due to reactive oxygen species (ROS) production (up to 5 g L^{-1})	Adams et al. (2006)

Source: Ditta et al. (2015), Li et al. (2015), Mura et al. (2015), and Thul and Sarangi (2015)

(a) It is found that, the application of nano-SiO_2 (up to 8 g L^{-1}) significantly improved seed germination of tomato, seed germination index, seed vigor index, seedling fresh weight and dry weight. Due to this application of nano-SiO_2, an increase in germination parameters may be effective for the growth and yield of crops. It could be suggested that, nano-SiO_2 could be used as a fertilizer for the crop improvement (Siddiqui and Al-Whaibi 2014).

(b) It is also reported that, nano-SiO_2 enhanced seed germination and stimulated the antioxidant system under NaCl stress in case of tomato (Haghighi et al. 2012) and for squash (Siddiqui et al. 2014).

(c) Under salinity stress, nano-SiO_2 improves leaf fresh and dry weight, chlorophyll content and proline accumulation. Due to the application of nano-SiO_2, it is found an increase in the accumulation of proline, free amino acids, content of nutrients, antioxidant enzymes activity, thereby improving the tolerance of plants to abiotic stress (Haghighi et al. 2012; Li et al. 2012; Siddiqui et al. 2014; Kalteh et al. 2014).

Several studies suggested that, zinc oxide nanoparticles (nano-ZnO) increased plant growth and development such as peanut (Prasad et al. 2012), soybean (Sedghi et al. 2013), wheat (Ramesh et al. 2014) and onion (Raskar and Laware 2014). These previous authors reported that, lower concentration of nano-ZnO exhibited a beneficial effect on seed germination. It is also found using different concentrations of nano-ZnO on cucumber, alfalfa and tomato, that only cucumber seed germination was enhanced (de la Rosa et al. 2013). Helaly et al. (2014) found that, nano-ZnO (up to 200 mg L^{-1}) supplemented with MS media promoted shooting, somatic embryogenesis, regeneration of plantlets, and also induced proline synthesis, activity of some enzymes including superoxide dismutase, catalase, and peroxidase thereby improving tolerance to biotic stress. Therefore, some researchers have been studied different toxicological effect of nanoparticles on plants due to their unique properties. Whereas, their research focused on the realization of the beneficial effects of nanoparticles on plant remains incomplete. Furthermore, few studies have shown a positive effect of nanoparticles on plant growth and development. It is proved that, effect of nanoparticles varies from plant to plant depending on their mode of application, size and concentrations by Siddiqui et al. (2015b).

It could be concluded that, nanoparticles have different effects on plants depending on several factors including plant species, nanoparticles and environmental factors. Further research is needed to confirm whether nanoparticles are essential for plants as well as the current researches are in the beginning. To understand biochemical, physiological and molecular mechanisms of nanoparticles in plants, more hard works are required.

10.5 Nanoparticles for Plant Nutrition

The applications of nanotechnology concerning applied materials sciences and biomass conversion technologies can be considered the basis of providing food, feed, fiber, fire, and fuels in agriculture. Therefore in agriculture, management of

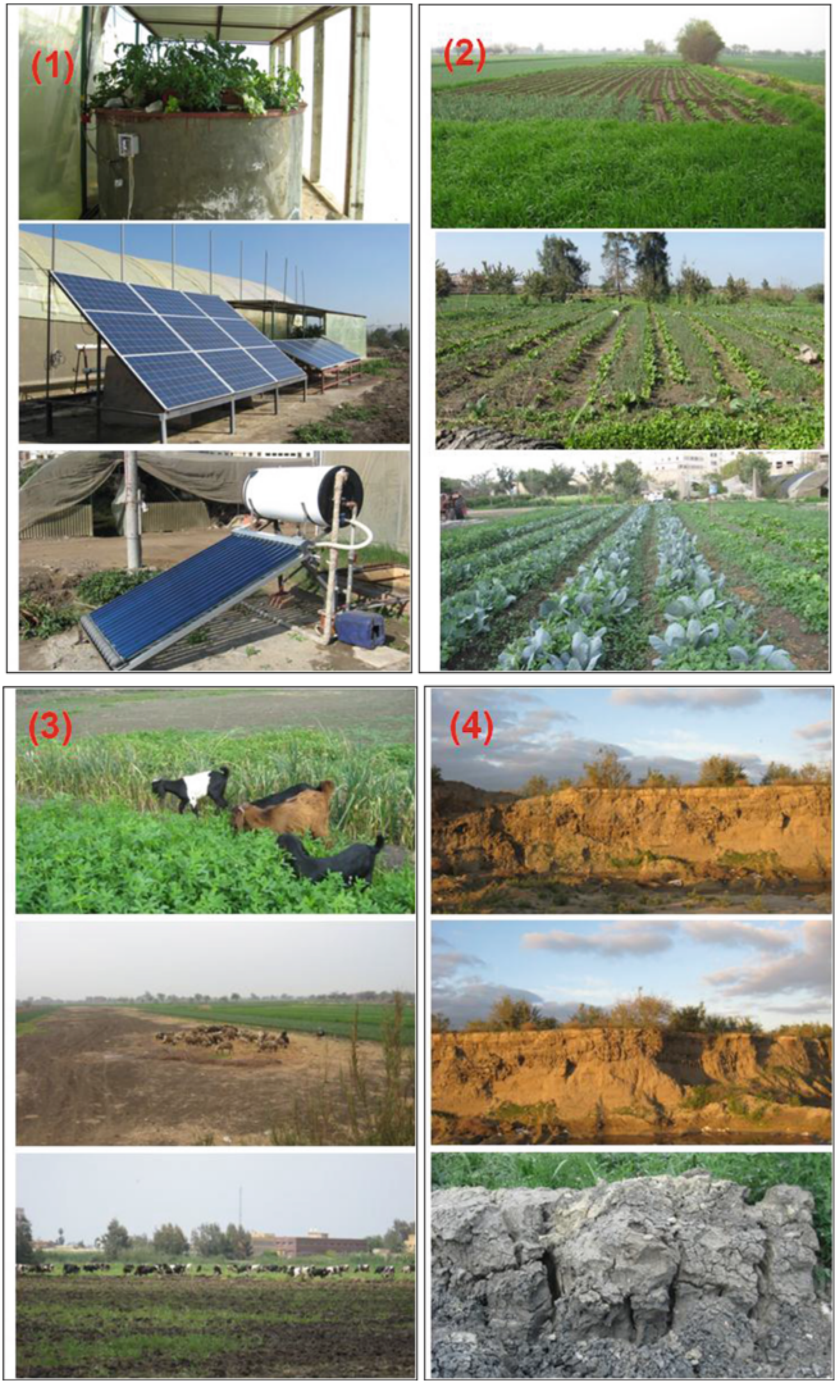

Fig. 10.3 Closed hydroponic system (vegetables and fish production) and solar energy system can be used in the experimentation farm in Kafrelsheikh Uni., (photo 1), intensive crop production (photo 2), livestock production system in Kafrelsheikh (photo 3) and sediments (NOT soil profile) from Burullus Lake (sandy soils) and main Gharbia drain (clay soils) during the cleaning process (photo 4) in Kafr El-Sheikh Governorate (Photos by El-Ramady)

Fig. 10.4 Soil management of salt-affected soils can be performed in strawberry (photo 1) and pepper (photo 2) production under green house (drip irrigation), to overcome their problems using soil amendments and solarization in Kafrelsheikh Uni (Photos by El-Ramady)

optimum plant nutrients for sustainable crop production is the priority-based area of research (Figs. 10.3 and 10.4). In this regard, much progress in the area of plant nutrition has come forward and nano-nutrition is one of the most interesting research areas for sustainable agriculture production (Ditta et al. 2015). Plant nano-nutrition is the application of nanotechnology for the provision of nano-sized nutrients for the crop production. It could be used of nanoparticles or nano-nutrients under two cases including biotic and abiotic forms. In regard to the abiotic form of nano-nutrients, it is prepared from inorganic sources like salts but due to many of them non-biodegradable, it is not safe. Concerning the biotic one, it is prepared from organic sources which are definitely environment friendly and biodegradable (Ditta et al. 2015). Therefore, a few attempts or studies have been made in the field of nano-nutrition and a lot more are expected in the near future because this field of plant nutrition is efficient and sustainable. Hence, it could be increased the efficiency of micro- as well as macro-nutrients for plants using this nano-nutrition (Ditta et al. 2015; Mastronardi et al. 2015; Servin et al. 2015; Thul and Sarangi 2015).

It is well documented that, nanotechnology has the potential to revolutionize the agricultural sector with novel tools for enhancing the productivity of the crop plants through efficient nutrients in the form of nanofertilizers, nanopesticides, or nanoherbicides by the plants (Tarafdar et al. 2013). Whereas, it could be enhanced the agricultural productivity by using of such nano-nutrients for formulation of nanofertilizers, nano-porous zeolites for slow release, enhanced germination, as well as efficient nanocapsules for herbicide delivery and vector; efficient dosage of water and fertilizer; pest management and nano-sensors for pest detection (Scrinis and Lyons 2007). These previous applications would definitely be helpful for the solutions of the limitations and challenges facing large scale and intensive farming systems (Ditta et al. 2015).

It is also reported that, nanomaterials have great implications in sustainable agricultural crop production and many studies reported their positive impact on various crops, whereas the main effect has been reported to be improved in these reports is the germination of various crops (Ditta et al. 2015). Concerning this effect on the germination of plants, some studies have been involved in improving the growth of crops by the application of different nano-nutrients such as nano-SiO_2 in maize and tomato (Suriyaprabha et al. 2012a, b; Siddiqui and Al-Whaibi 2014), carbon nanotubes in tomato, mustard and rice (Khodakovskaya et al. 2009; Nair et al. 2010; Ghodake et al. 2010), nanao-TiO_2 in spinach and wheat (Lei et al. 2008; Feizi et al. 2012; Larue et al. 2012), and nano Si, Pd, Au, Cu in lettuce (Shah and Belozerova 2009). Therefore, it could be summarized the effects of nanonutrients or nanofertilizers on the growth, germination rate, phytotoxicity and other physiological characterizations for certain common vegetable and field crops as follows:

1. Barley (*Hordeum vulgare* L.): Chauhan et al. (2013), Gruyer et al. (2014), Rico et al. (2015), and Feichtmeier et al. (2015);
2. Chickpea (*Cicer arietinum* L.): Burman et al. (2013), Mohammadi et al. (2013, 2014), Nair and Chung (2015b), and Hasanpour et al. (2015);
3. Cabbage (*Brassica pekinensis* L.): Baskar et al. (2015) and Xiang et al. (2015);
4. Cucumber (*Cucumis sativus* L.): Kim et al. (2012), Shams et al. (2013), Cui et al. (2014), Haghighi and da Silva (2014), and Zhang et al. (2015);
5. Green pea (*Pisum sativum* L.): Huang et al. (2014), Mukherjee et al. (2014), and Nair and Chung (2015a);
6. Lettuce (*Lactuca sativa* L.): Song et al. (2013), Gruyer et al. (2014), Gui et al. (2015b), Doolette et al. (2015), Hong et al. (2015), and Zahra et al. (2015);
7. Maize (*Zea mays* L.): Suriyaprabha et al. (2012a, b), Sun et al. (2014), Liu et al. (2015), and Zhang et al. (2015);
8. Oil seed rape (*Brassica napus* L.): Song et al. (2013), Kouhi et al. (2015a, b), Palmqvist et al. (2015), and Sarabi et al. (2015);

9. Onion (*Allium cepa* L.): Golubkina et al. (2012), Haghighi and da Silva (2014), Laware and Raskar (2014), Konotop et al. (2014), and Taranath et al. (2015);
10. Rice (*Oryza sativa* L.): Nair et al. (2011), Shaw and Hossain (2013), Rico et al. (2013a, b), Gui et al. (2015a), Da Costa and Sharma (2015), and Wang et al. (2015b);
11. Tomato (*Solanum lycopersicum* L.): Haghighi et al. (2012), de la Rosa et al. (2013), Faisal et al. (2013), Haghighi and da Silva (2014), Siddiqui and Al-Whaibi (2014), Shankramma et al. (2015), Antisari et al. (2015), and Mehrian et al.(2015);
12. Turnip (*Brassica rapa* ssp. rapa L.): Thiruvengadam et al. (2015);
13. Wheat (*Triticum aestivum* L.): Du et al. (2011), Larue et al. (2012), Feizi et al. (2012), Cui et al. (2014), Yanık and Vardar (2015), Wang et al. (2015a), and Watson et al. (2015).

An increase in the germination rate of the previous stated crops is an important aspect of the nanomaterials however, the application of these nanomaterials as a nutrient source for the entire growth cycle of two crop plants needs to be explored yet. So, the evaluation of these materials as a nutrient source, their critical concentration, and their phytotoxic effects, if any need to be explored in future (Ditta et al. 2015).

Recently, several studies have been focused on the interaction between nanoparticles and different plant species including the physiological, phytotxicological and biochemical aspects as well as plant nutrition (Patra et al. 2013; Seabra et al. 2014; Taran et al. 2014; El-Ramady et al. 2014a, b, 2015b, c, d, 2016; Ditta et al. 2015; Subramanian et al. 2015; Dimkpa et al. 2015; Da Costa and Sharma 2015, Mastronardi et al. 2015; Monreal et al. 2015; Solanki et al. 2015). So, plant nanonutrition and nanofertilizers as well as nanophytoremediation are emerging issues should be considered in frame of sustainable agriculture. Extensive studies had been undertaken to study different nanoparticles containing nutrients in frame of plant nutrition as follows:

1. Nitrogen-nanofertilizers (Subramanian and Sharmila Rahale 2013; Mohanraj 2013; Manikandan and Subramanian 2014; Seabra et al. 2014),
2. Phosphate-nanofertilizers (Bansiwal et al. 2006; Adhikari 2011; Behnassi et al. 2011; Liu and Lal 2014),
3. Potassium-nanofertilizers (Subramanian and Sharmila Rahale 2012),
4. Sulfur-nanofertilizers (Patra et al. 2013; Selva Preetha et al. 2014; Thirunavukkarasu 2014),
5. Calcium oxide nanoparticle (Deepa et al. 2015), iron oxide nanoparticle (Kim et al. 2015),
6. Magnesium nanofertilizers (Delfani et al. 2014),
7. Copper oxide nanoparticles (Da Costa and Sharma 2015; Dimkpa et al. 2015),
8. Manganese nanoparticles (Pradhan et al. 2014),
9. Zinc oxide nanoparticles (Subramanian and Sharmila Rahale 2012; Patra et al. 2013; Tarafdar et al. 2014; Dimkpa et al. 2014, 2015; Watson et al. 2015),

10. Silicon nanoparticles (Siddiqui and Al-Whaibi 2014; Kalteh et al. 2014; Le et al. 2014; Abdul Qados and Moftah 2015; Abdul Qados 2015),
11. Molybdenum (Aubert et al. 2012; Taran et al. 2014; Kanneganti and Talasila 2014),
12. Iron oxide (Alidoust and Isoda 2013; Ghafariyan et al. 2013; Lebedev et al. 2014; Soliman et al. 2015; Shankramma et al. 2015),
13. Nickel oxide (Faisal et al. 2013; Oukarroum et al. 2015; Antisari et al. 2015) and
14. Selenium nanoparticles (Golubkina et al. 2012; Husen and Siddiqi 2014; El-Ramady et al. 2015b, c, d, 2016; Papkina et al. 2015).

For more an efficient use of agricultural natural resources like water, nutrients, and chemicals during farming, nanotechnology (like nano-sensors) gave us the ability to develop and maximize the benefits of these resources management. Moreover, these nano-sensors, which have been proved to be user friendly, have not only been used as nano-biosensors but also for the control of soil nutrients and these have helped in the reduction of fertilizer consumption and environmental pollution (Ingale and Chaudhari 2013; Ditta et al. 2015; Kah 2015).

Therefore, it is well established that, nanotechnology has great potential in improving the quality of life through its applications in various fields including agriculture production and food system. Moreover, the nanomaterials have been applied as nano-nutrients (in the form of nanofertilizers) for crop production and as crop protectants in the form of nanopesticides and nano-herbicides, as well as nano-sensors in precision agriculture. In this regard, the importance of nano-nutrition in the sustainable agricultural production and its future scenario could be possible to apply on a large scale. Nevertheless, nanotechnology has a great potential in various walks of life, but we must be very careful about any new technology to be introduced for its possible unforeseen related risks that may come through its positive potentials. Therefore, potential applications of nanotechnology in agricultural production for the welfare of humans and hence sustainable environment, challenges, and opportunities for developing countries should be kept in mind.

It could be concluded that, nanoparticles are emerging issues for plant nutrition in the frame of sustainable agriculture. These nanoparticles can be considered an important source for nano-nutrition of plants and nanofertilizers. Otherwise, there are some open questions still in needing to answer including: (1) are nano-nutrients or nanofertilizers enough or sufficient sources for crop production instead of normal mineral fertilizers? (2) To what extent are the different effects of nanofertilizers currently taken into account? (3) Can different risks and benefits associated with the use of nanofertilizers be assessed? (4) Which nanofertilizer types are ready to emerge in the forseen future under different regulations?

10.6 Conclusion

The aim of this review is to explore the potential of the field of nanoparticles with respect to sustainable agriculture. This main focus is on the currently applied uses of nanoparticles for agriculture including different effects in enhancing soil security, using of nanoparticles for plant nutrition as well as nanoparticles and its effects on plants. Nanoparticles have emerged as a versatile platform, which could provide cost-effective, efficient and environmentally acceptable solutions to the global sustainability challenges facing society. Nanoparticles have a significant influence on the economy and the environment by improving both fertilizers and energy. So, these nanoparticles have a high potential for achieving sustainable agriculture. Therefore, the agri-nanotechnology might take a few decades to move from laboratory to land.

Acknowledgements Authors thank the outstanding contribution of STDF research teams (Science and Technology Development Fund, Egypt) and MBMF/DLR (the Federal Ministry of Education and Research of the Federal Republic of Germany), (Project ID 5310) for their help. Great support from this German-Egyptian Research Fund (GERF) is gratefully acknowledged.

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