Chapter 1
Agricultural Nanotechnologies: Current Applications and Future Prospects

Rout George Kerry, Sushanto Gouda, Gitishree Das, Chethala N. Vishnuprasad, and Jayanta Kumar Patra

1.1 Introduction

The planet earth is inhabited by over seven billion people within the land area of 13 billion hectares, for which 99.7% food comes from the terrestrial ecosystem. As per Food and Agriculture Organization [FAO] (2017) data sheet more than 4.9 million hectares of land that constitute 37.6% of the terrestrial ecosystem is encapsulated for agricultural purposes. The fact that terrestrial land masses are the sole provider of the basic necessities of life makes every inch of landmass an important component for food source. Globally 30% of the workers are involved in farming, but in low-income countries it rises to about 60% (FAO 2017). In 2016, 54.5% of the world population were living in urban areas but by 2030, it is estimated that 60% of world's population will be shifting to urban areas (The World's Cities 2016). This shift may pose an indirect but a permanent threat as rural areas or farm lands and the farmers are the only suppliers of the food for the present generation as well as to the future generation which is expected to reach 11 billion by 2100. Even though farmers are the backbone of various countries, in India and in many other developing countries farmers face malnutrition as well as several other economic issues like

R.G. Kerry
P.G. Department of Biotechnology, Academy of Management & Information Technology, Khurda, Odisha, India

S. Gouda
Amity Institute of Wildlife Science, Amity University, Noida, Uttar Pradesh, India

G. Das • J.K. Patra (✉)
Research Institute of Biotechnology & Medical Converged Science, Dongguk University-Seoul, Ilsandong-gu, Gyeonggi-do, South Korea
e-mail: jkpatra@dongguk.edu

C.N. Vishnuprasad
School of Integrative Health Sciences, Institute of TransDisciplinary Health Sciences and Technology, Bangalore, Karnataka, India

J.K. Patra et al. (eds.), *Microbial Biotechnology*,
https://doi.org/10.1007/978-981-10-6847-8_1

doughty, high price of fertilizers, poor rainfall, less productivity etc. that even lead to suicide (NCRB ADSI annual reports 2013, 2014, 2015).

Statistics shows that currently 78% of under-privileged people worldwide are from rural areas and around 800 million people are suffering from hunger. If the current scenario is unaltered by 2030, then 653 million people will remain undernourished (FAO 2017; World Bank 2017). Although government agencies are working on improvement and development of farmers through different schemes and if the present situation still continues, then it would result in an unsustainable and irreversible imbalance in the supply of farm or agricultural products. Conventional techniques or measures taken by various government agencies across the globe are mostly restricted to providing loans, fertilizers, electricity for irrigation, improved crop seeds etc. However, all such measures are irrelevant and incapable in case of soil infertility, plant diseases and poor crop yield. Such situations continue to persist and proper scientific knowledge and technologies need to be created for agriculture activities (Srilatha 2011). Practise of monoculture or single crop plantation has also been considered as a major reason behind soil infertility and poor agricultural production. Hence, use of modern tools and techniques, science for successful plantation, good knowledge about soil, development of diseases resistant crops and production of nutrient containing crops or grains are some of the areas to be considered with immediate priority.

In the sea of the opportunities, it is impossible for the cargo to sail towards prosperity without lifting the anchor of poverty. Despite the flexibility and implementation of technology in different fields such as industrialization, biomedical research, ceramics, remote sensing, space technology, application of science and technology for sustainable agricultural development is the most important as it is the most successful and reliable source of production of any type of food, for both humans and animals. Therefore, the focus of every nation should be to find diverse and novel ways, through exploring multidisciplinary and interdisciplinary technologies such as biotechnology, nanotechnology, nano-biotechnology etc., to improve agriculture and crop production (Gul et al. 2014; Srilatha 2011). Amalgamated technology such as nanotechnology holds promising results in different aspects of agriculture through nano-formulations of agrochemicals *viz.* pesticides, insecticides, herbicide, nanobiofertilizers etc., formation of nanosensors/ nanobiosensors, crop improvement strategies, protection and identification of diseases, genetic manipulation of crop plants, improvement of health and breeding techniques of animal and poultry, post-harvest management with smarter, stronger and cost-effective techniques. (Fig. 1.1; Table 1.1) (Wang et al. 2016; Yearla and Padmasree 2016; Sekhon et al. 2014).

Nanotechnology has also been applied in identification of elite genes and their use in crop improvement to for high productivity and disease resistance (Cheng et al. 2016). Similarly, nanotechnology is also used in the health improvement and breeding of animals as well. Besides, the applications of nanotechnology also include nanosensors for accurately reporting the physiological conditions of soil and carbon based nanocarriers for targeted drug delivery, for increasing nutrient uptake, induction of better production etc. (Thornton 2010). As nanotechnology is an interdisciplinary field of science, it has vast diversity of applications in the field of sustainable development of agriculture. Henceforth, the present chapter is more

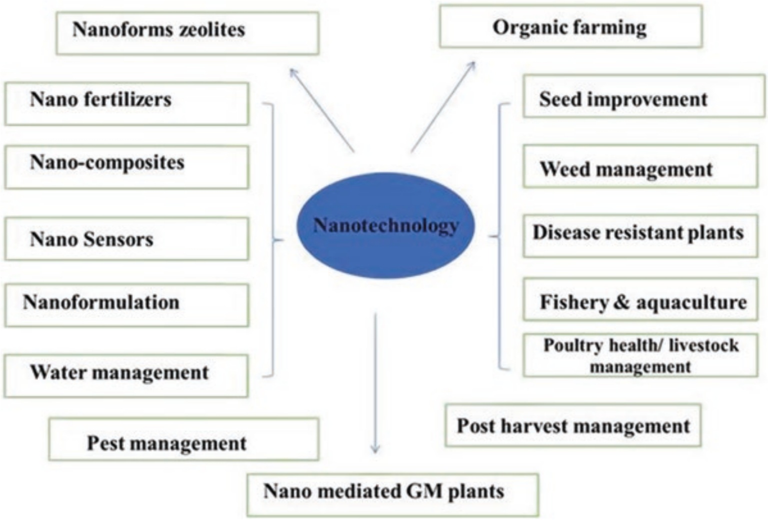

Fig. 1.1 Different fields where nanotechnology has potential application in agriculture

dedicated towards outlining the relevance of nanotechnology in the present day agricultural applications and its future prospective.

1.1.1 Nanoformulations

Nanoformulations alone cannot be considered as a single entity as they are combination of several surfactants, polymers (natural and artificial organic compounds), and metal nanoparticles in nanosize range. Pesticides made up of imidacloprid (1-(6 chloro-3-pyridinyl methyl)-N-nitro imidazolidin-2-ylideneamine), fungicides composed of hexaconazole encapsulated by chitosan nanocapsule, herbicides consisting of optimized diuron, insecticides from polycaprolactone and poly(lactic) acid nanospheres are some of the nanoformulations that are readily used in development of agriculture productivity (Adak et al. 2012; Chauhan et al. 2016; Yearla and Padmasree 2016; Boehm et al. 2003).

1.1.2 Nanofertilizers

Nanofertilizers are having growing demand in contrast to the common chemical fertilizers. Nanofertilizer includes the use of various inorganic compounds like iron oxide nanoparticles for iron deficiency, titanium dioxide nanoparticle, and silicon dioxide nanoparticles for plant growth and nourishment (Wang et al. 2016; Lu et al. 2002). Nanofertilizers have several advantages over conventional

Table 1.1 Uses of various nanoparticles in diversified agricultural sector

Nanoparticles	Applications	References
CeO_2	Stress response and tolerance of *Zea mays*	Zhao et al. (2012)
Fe_2O_3	Insecticide in Bt-transgenic and non-transgenic cotton	Nhan et al. (2015)
AgNPs/ oxMWCNTs	Insecticide	Hsu et al. (2017)
Bionanocomposite materials	Light energy conversion (e.g., photovoltaics) or biosensing (e.g., for specific detection of pesticides)	Nagy et al. (2014)
Carbon-coated Fe nanoparticles	Smart treatment-delivery systems in plant tissue	González-Melendi et al. (2008)
Cellulose nanofibers	Biomedical application such as tissue engineering	Lima et al. (2012)
Cerium oxide and titanium oxide	As nano-fertilizer and nutrient enhancement in *Hordeum vulgare* L.	Poscic et al. (2016)
Copper (II) oxide (CuO) and multiwall carbon nano-tubes (MWCNTs)	Detection of glyphosate in water	Chang et al. (2016)
Cu $(OH)_2$ nanopesticides	Enhancement of nutritional value of *Lactuca sativa*	Zhao et al. (2016)
Engineered water nanostructures	Antimicrobial platform for food safety	Pyrgiotakis et al. (2016)
Fe_2O_3	Nano-fertilizer in *Arachis hypogaea*	Rui et al. (2016)
Fullerene, C_{60} and carbon nanotubes	Increase the water retaining capacity, biomass and fruit yield in plants	Husen and Siddiqi (2014)
Gold NP-based electrochemical biosensor	Rapid and sensitive detection of plant pathogen DNA	Lau et al. (2017)
Magnesium hydroxide (Mg $(OH)_2$) nanocomposites	Efficient bioactive packaging of goods	Moreira et al. (2013)
Multi-walled carbon nanotubes (MWCNTs)	Contaminant carriers and translocate within *Brassica juncea*	Chen et al. (2015)
MWCNT and cotton CNF	Show ecotoxicological effects by inducing viability of *Chlorella vulgaris*	Pereira et al. (2014)
Nano air bubbles	Hydroponic growth of *Brassica campestris*	Ebina et al. (2013)
Nano-biosensors	Labelling products and automated storage	Ali et al. (2017)
Nanochitosan	Supports growth of *Zea mays* and also maintains soil health	Khati et al. (2017)
Nanodiagnostic kit	Plant pathogen detection	Khiyami et al. (2014)
Nanostructured lipid carriers	Antimicrobial activity	Cortesi et al. (2017)
NP-based sensors	Assessing food safety	Bulbul et al. (2015)
Optimized diuron nanoformulation	Nanoherbicide	Yearla and Padmasree (2016)

(continued)

Table 1.1 (continued)

Nanoparticles	Applications	References
Poly (γ-glutamic acid (γ-PGA) and chitosan (CS) polymers based NPs	Nanofertilizers	Pereira et al. (2016)
Protein	Nanoencapsulation of hydrophobic nutraceuticals. Improved functionalities in casein micelle (Meat processing)	Semo et al. (2007)
Quaternized chitosan-capped mesoporous silica NPs	Fungicidal activity against *Phomopsis asparagi*	Cao et al. (2016)
Silver	Control of *Colletotrichum* species	Lamsal et al. (2011)
Thermoplastic starch/ urea medleys as a matrix with hydroxyapatite as nanocomposites	Nanofertilizers	Giroto et al. (2017)
Vitamin D_3-loaded nanostructured lipid carriers (NLCs)	Fortifying food beverages	Mohammadi et al. (2017)
Zinc oxide	Transparent electronics, ultraviolet (UV) light emitters, piezoelectric devices, chemical sensors, spin electronics, enhance crop growth	Sabir et al. (2014)

chemical fertilizer due to their small size, large surface area to act and easy penetration in soil through soil porous.

1.1.3 Nanosensors

Nanosensors/ nanobiosensors are emerging as rising advantageous tools for the application in the field of agricultural research and production which have normal arrangements like ordinary sensors but only vary their size at nano scale level (Omanovic-Miklicanin and Maksimovic 2016). Nanosensors are alternative to conventional methods due to their high sensitivity, selectivity, low detection limits, fast response and small size. Nanosensors are mostly used for detecting pesticide residues and other residues of agrochemicals which is again backed up by certain morphological and economics properties such as ease of miniaturization, electrochemical, optical properties that is further simple and cost-effective (Wang et al. 2016; Cheng et al. 2016).

1.1.4 Nanomaterials

Crop improvement has also been made possible by the use of natomaterials such as carbon nanotubes and other in organic nanoparticles such as gold, SiO_2, TiO_2, ZnO which directly or indirectly helps in nutrient (element) uptake by the plant (Khot et al. 2012). Certain other metallic nanoparticles like silver and copper have shown antimicrobial properties, polymer-based copper nano-compound, silica-silver nanoparticles have been investigated with antifungal properties and for control of certain plant disease like pumpkin disease (Gul et al. 2014).

1.2 Modern Techniques Implemented for Development in Agriculture

Development and improvement of agriculture has for long been dependent on the associated biotic and abiotic components that largely influence the agricultural productivity. Some of these associated components are deteriorating due to the various forced procedure of unsustainable farming such as soil qualities (texture, water retention capacity, nutrient content etc.), crop quality (diseased crops), water availability and quality (Rajonee et al. 2017; Omanovic-Miklicanin and Maksimovic 2016; Cheng et al. 2016). Such forms of impacts are direct results of unmaintained and unsafe agricultural practices for selfish sustenance and can be overcome with the use of modern techniques. Some of these techniques involve the use of interdisciplinary science and research. Currently nanotechnology is a booming field of science like a “philosopher’s stone” which is a legendary substance that have capacity to turn any inexpensive metals into gold when combined or touched. Similarly, in the field of research and development, when nanotechnology is combined with any field of science or technology, gives most spectacular and promising results, that is of gold standard. Moreover, in agricultural sector nanotechnology has revolutionized the standards of agriculture by development of soil quality, crop quality, sensing unnecessary agronomical debris, maintenance the productivity and disease progressiveness in the plants as well as or poultry animals and bards, effective and targeted gene manipulation within these farm flora and fauna of agricultural importance, and finally postharvest management with smarter, stronger, cost-effective packaging of these farm/ agricultural products (Wang et al. 2016; Khot et al. 2012; Srilatha 2011). There are many more potential applications of nanotechnology in the agriculture sector (Tables 1.1 and 1.2; Fig. 1.2), which has been subsequently discussed in this chapter.

Table 1.2 Examples of significant applications of nanotechnology in agriculture sector

	Definition	Example	Reference
Crop production			
Plant protection products	Nanocapsules, nanoparticles, nanoemulsions and viral capsids as smart delivery systems of active ingredients for disease and pest control inplants	Neem oil (*Azadirachta indica*) nanoemulsion as larvicidal agent (VIT University, IN)	Anjali et al. (2012)
Fertilizers	Nanocapsules, nanoparticles and viral capsids for the enhancement of nutrients absorption by plants and the delivery of nutrients to specific sites	Macronutrient fertilizers coated with zinc oxide nanoparticles (University of Adelaide, AU CSIRO land and water, AU Kansas State University, US)	Milani et al. (2015)
Water purification			
Water purification and pollutant remediation	Nanomaterials, e.g. nano-clays, filtering and binding to a variety of toxic substances, including pesticides, to be removed from the environment	Filters coated with TiO_2 nanoparticles for the photo catalytic degradation of agrochemicals in contaminated waters (University of Ulster, UK)	McMurray et al. (2006)
Diagnostic			
Nanosensors and diagnostic devices	Nanomaterials and nanostructures (e.g. electrochemical lyactive carbon nanotubes, nanofibers and fullerenes) that are highly sensitive bio-chemical sensors to closely monitor environmental conditions, plant health and growth	Pesticide detection with a liposome-based nano-biosensor (University of Crete, GR)	Vamvakaki and Chaniotakis (2007)
Plant breeding			
Plant genetic modification	Nanoparticles carrying DNA or RNA to be delivered to plant cells for their genetic transformation or to trigger defense responses, activated by pathogens.	Mesoporus silica nanoparticles Transporting DNA to transform plant cells (Iowa State university, US)	Torney et al. (2007)
Nanomaterials from plant			
Nanoparticles from plants	Production of nanomaterials through the use of engineered plants or Microbes and through the processing of waste agricultural products	Nanofibres from wheat straw and soy hulls for bio-nanocomposite production (Canadian Universities and Ontario Ministry of Agriculture, Food and Rural Affairs, CA)	Alemdar and Sain (2008)

Source: Parisi et al. (2015)

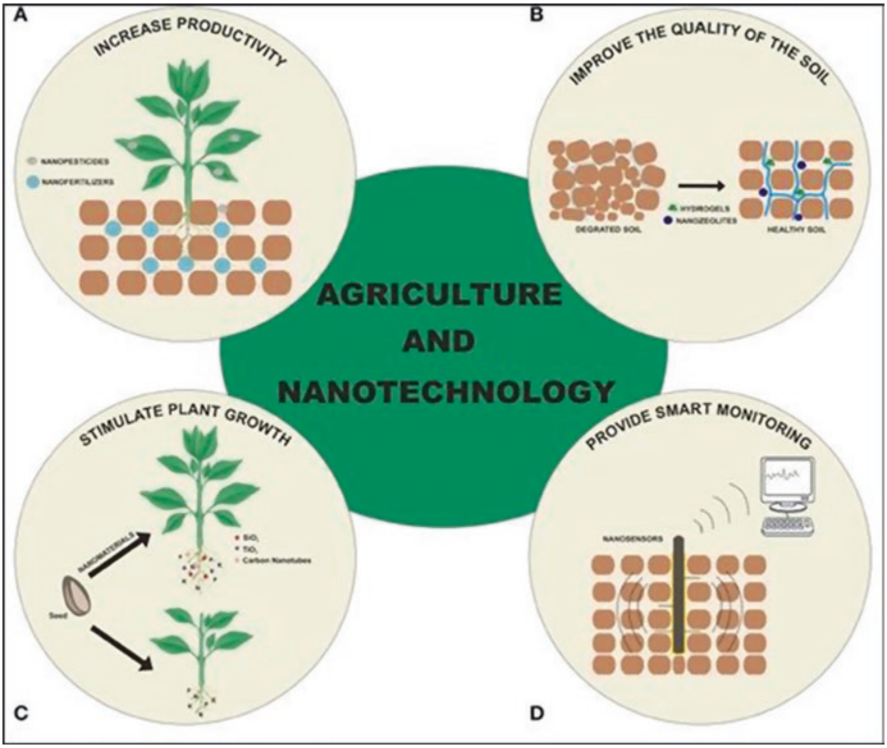

Fig. 1.2 Application of nanotechnology in agriculture. (**a**) for increasing productivity, (**b**) for improvement of the quality of soil, (**c**) for stimulating plant growth and (**d**) for providing smart monitoring (Source: Fraceto et al. 2016)

1.2.1 Nano-Formulations of Agrochemicals

Nanoformulation is a mixture of different particles which gives rise to a single particle of nano range. The mixture in general is composed of several surfactants which stabilizes the formulation either by ionic or non-ionic interaction, polymers (natural and artificial organic compounds), and metal nanoparticles that serves as a carrier or container of the active component of the nanoformulation (Sekhon et al. 2014). Together with the surfactant, the carrier and the active is referred to as a nanoformulation. But when the active component in the nanoformulation is agronomically important compound or substance then the whole formulation can be referred to as nanoagrochemical (Adak et al. 2012; Boehm et al. 2003). The nature of the nanoagrochemical depends on the function or the purpose of the type of agronomically active compound or substance they withhold or composed, for instance the formulation of nanopesticides, nanoherbicides, nanoinceticides and nanofertilizers.

1.2.2 Nanotechnology in Pesticides

Currently nanopesticides that are copper based are widely being used, in comparison to conventional pesticides, in agriculture particularly in organic farming. Zhao et al. (2016) studied metabolomics application of Cu $(OH)_2$ nanopesticides on the nutritional value of *Lactuca sativa* and along with the help of certain sophisticated high-throughput instrumentation and technology such as Gas chromatography-Time-of-Flight-Mass Spectrometry (GC–TOF-MS) based metabolomics approach and Partial Least Squares-Discriminant Analysis (PLS-DA). They also emphasized that the deposition of copper in the vascular bundle of leaves for foliar application. These levels of copper deposition were recommended guidelines including increased concentration of certain minerals specifically potassium as well as upregulation of physiologically important proteins, vitamins, and phytohormones. Optimized Diuron Nano Formulation (ODNF) is a stable nanoherbicide made from diuron (1,1-dimethyl, 3-(3′,4′-dichlorophenyl) urea) and stem lignin as a matrix of *Leucaena leucocephala* for control release of this nanoformulation. Diuron (1,1-dimethyl, 3-(3′,4′-dichlorophenyl) urea) is herbicide, inhibits plant photosynthesis and growth. Diuron activity can be further increased by the help of nanotechnology. Due to its small size, inhibiting the metabolic functions of the seedlings until 16 weeks without losing its activity successfully leads to chlorosis and mortality. ODNF not only function as herbicide but also protects the active ingredient from microbial degradation, UV damage (Yearla and Padmasree 2016). Hexaconazole based *Controlled-released Nitrogen Fertilizers* (CRNF) are the nanoformulation used for the controlled release of hexaconazole. It consists of a fungicide called hexaconazole encapsulated by chitosan nanocapsule that is a combination of chitosan and is synthesized from naturally occurring chitin by partial N-deacetylation with alginate and tripolyphosphate. It is a fungicide that is extensively used for controlling fungal pathogens on various crops mainly against *Rhizoctonia solani*. Besides its fungicidal activity hexaconazole show herbicidal activity and also has major effects including reduction in shoot length, leaf area, and whole dry weight in the case of some *Plectranthus* spp. (Chauhan et al. 2016). Nanostructured Lipid Carriers (NLC) is a nano formulation known for encapsulating natural molecules having antimicrobial activity such as plumbagin, hydroquinon, eugenol, alpha-asarone, and alpha-tocopherol. The NLC were prepared by melting and ultrasonication method, characterized by Cryo-TEM for morphology and SdFFF for dimensional distribution and active encapsulation yields. The efficiency of the system could be mainly described by its efficiency in controlling the phytopathogen. The NLC produced by using blends of solid (e.g. triglycerides) and liquid (e.g. tricaprylin) lipids at ambient temperatures increase solubility and enhances the efficiency of natural antimicrobial molecules. It only gives protective encapsulation for delivery and increases solubility leads to rapid penetration (Cortesi et al. 2017).

It has been previously acknowledged these nano-agroformulations showing more promising results compared to traditional or conventional formulations. Bifenthrin, a pyrethroid insecticide has also been developed, which is neurotoxic to both insects and mammals but its activity dynamically modulated in its nanoformulated form. In a case study conducted by Kah et al. (2016) showed that nanoformulations had remediating effect on its soil absorption and degradation. But the ability of controlled release is not clear. Therefore, further investigation is necessary to evaluate the efficiency of these nano-formulations both on biotic and abiotic components of the parameters influencing agricultural practices.

1.2.3 Nanotechnology in Fertilizers

Presently the synthesis and application of nanoparticles have taken a discreet turn in various field of agricultural science, but when particularly considered to the dynamic nature of soil and its fertility, nanoparticleshave certainly proved their potential. Nanoparticles based fertilizers or in a single term nano-fertilizers such as phosphate, nitrogen, iron, zinc, titanium, aluminium, copper, and silver based nano-fertilizers have tremendously shifted the goal of sustainable agriculture to the next higher level (Malik and Kumar 2014). Some of these nano-fertilizers have been effectively used to improve agricultural products along with sustaining the biotic and abiotic factors associated with farming. Recently a greenhouse experiment was conducted to evaluate the impact of these nano-fertilizers on the production of total phenolic content, and antioxidant activity of rice. In a particular study the efficacy of nano-fertilizers (FRR-CF+FRR-NF) on plant at different stages starting right form seedling, tillering and till panicle initiation stage was evaluated. It was found that FRR-CF+FRR-NF significantly enhanced the plant height, chlorophyll content and the number of reproductive tillers, panicles, and spikelets (Benzon et al. 2015). Nano iron is another example of nanofertilizer, important nanoformulation against Fe deficiency and show Fe fertilization effect in agricultural applications.

Treatment of iron oxide nanoparticles (Fe_2 O_3 NPs) to soil with different concentration showed significant physiological changes in content of soluble sugar and protein, content of chlorophyll and malondialdehyde (MDA), and activity of antioxidant enzymes of watermelon leaves. Proper concentration of Fe_2O_3 NPs has the ability to improve iron deficiency chlorosis and enhance growth of watermelon plant. Studies show that chlorophyll content increases upon exposure to iron-based nanoparticles and thus the growth of certain plant such as *Lactuca sativa* could be significantly increased (Wang et al. 2016). Poly (γ-glutamic acid (γ-PGA) and chitosan (CS) polymers based nanoparticles are currently exploited for their advancement in drug delivery system as a carrier of the phytohormone (gibberellic acid) that regulates plant growth. In general gibberellic acid has several uses in the field such as improvement in the germination and development, plants along with enhancement in their productivity and quality. But upon encapsulating the same phytohormone has higher efficiency than normal phytohormones resulting in increase of leaf area and induction of root development. This phenomenon has been studied in *Phaseolus vulgaris* where γPGA/CS-nano encapsulation of the hormone gibberellic acid as thenano particles favoured the germination of the plant (Pereira et al. 2016).

In another study phosphorus (P) and potassium (K) incorporated nano-fertilizer was prepared, characterized by X-ray diffraction (XRD) and its efficiency was evaluated in a pot culture experiment with *Ipomoea aquatic*.

Zeolite a microporous, aluminosilicate minerals was used for nano-fertilizer synthesis by modification with certain surfactants. The study further concluded that nano-fertilizers efficiently contributed to the growth of the plant as well as to the accumulation P and K. Post-impact of the application of nano-fertilizers on soil showed improved pH, moisture, cations-exchange capacity and micro-nutrients retention capacity (Rajonee et al. 2017). It has been assumed that nano-fertilizers could play an indispensable effective role in increasing agronomic productivity without hampering the natural longitivity agronomic associated factors.

1.2.4 Application of Nanosensors/Nanobiosensors in Sustainable Agriculture

Sensors are the interface between the real and the virtual/ digital world. They are slowly and steadily amalgamating with versatile emerging technologies in inter or multidisciplinary fields of science and research to dynamically transcend the current evaluation of the magnificent nature along with the miraculous life within it. Commonly a sensor can be defined as a physical instrument used to measure physical properties, record, track, indicate or otherwise respond to it (Schneider et al. 2015). The three basic components of a sensor are detector, amplifier and transducer (Arlett et al. 2011; Rai et al. 2012). Based on the origin, type and the mode of detection these sensors can be segregated into different groups such as photo sensors, electrical sensors, chemical sensors or biological sensors (Rai et al. 2012; Turner 2013). Moreover, all these sensors can be further called as nano-sensors if their size falls within the nano range (Rai et al. 2012). Due to the small size, nano-sensors could be more efficiently exploited in heterogeneous filed for the benefit of mankind. Currently the use of these nano-sensors in the field of agriculture has made influential embellishments that forced the present thinkers to rethink the whole traditional processes of framing and adapt this spectacular piece of technology and integrate it into the farming (Omanovic-Miklicanin and Maksimovic 2016). Henceforth the nanotechnology based nano-sensors are employed in detection of residues of agrochemicals, crop improvement, protection and identification of diseases (Khot et al. 2012; Wang et al. 2016; Cheng et al. 2016).

1.2.4.1 Application in Detection of Residues of Agrochemicals

Agrochemical residues are those chemical components of the pesticides or the pesticide itself which gets accumulated in the field or the crops harvested from the field (Bhandari 2014). Food and Drug Administration (FDA) have detected 1045–1603 chemicals designated as pesticide residues (FDA 2005). In another FDA report of 2014 fiscal year a total sample of 6638 were analysed of both human and animal foods, where 705 pesticides and industrial chemicals were detected by the FDA (FDA 2014).Despite the significance of agrochemicals in efficient farming, they leave a trail of their despicable virtue that devours the fruitfulness sustainable agriculture. The over use of these chemicals have serious impact on the surrounding or the whole ecological habitat which may lead to immediate but chronic, catastrophic and irreversible modulations on the sustenance of agricultural productivity. A simple but yet effective remedy for stabilizing this patronizing deteriorative phenomenon is possible by the means of certain miniature devices based on nanotechnology (Bhandari 2014). These devices could efficiently detect the residues and simultaneously neutralize the threat and report.

These devises are generally called as sensors or more specifically nano-sensors because of the miniature size. They offer profound serviceability by their high sensitivity, super selectivity, fast responses and low detection limits. Nano-sensors have already been used for detection of some of the pesticide residues such as methyl parathion, parathion, fenitrothion, pirimicarb, dichlorvos and paraoxon (Khot et al. 2012). In the present scenario, an efficient mode of sensing such as luminescence had significantly increased the serviceability of these nano-sensors. Vasimalai and John (2013) had developed and studied a luminescent sensor using chitosan capped silver nanoparticles as a fluorophore for detection of malathion. The yellow color of the nanoparticle formulation changed to brown and a sharp decrease in the absorbance along the redshift. The nano-sensor was again applied for the determination of malathion in fruits and water samples the result of which further supported and validated by HPLC.

Recently a turn-off sensor was developed for measuring glyphosate using amalgamated form of copper (II) oxide (CuO) and multiwall carbon nano-tubes (MWCNTs), the efficiency of which was indicated by the decreased catalytic activity of the CuO/MWCNTs. The sensor showed promising efficiency in detection of glyphosate in water (Chang et al. 2016). Another marvelous detection method of dimethoate by the use of newly developed oxidized multi-walled carbon nanotubes (oxMWCNTs) modified with silver nanoparticle (AgNPs) having peroxidase-like activity further proved the extent to which nanotechnology could be exploited. Excellency of these synthesized nano-sensor's(AgNPs/ oxMWCNTs) peroxidase-like activity was verified by hydrogen peroxide-Amplex red system and it was found that, the catalytic activity of AgNPs/ oxMWCNTs decreased in the presence of dimethoate, because the insecticide effectively interacted with AgNPs of the nano-formulation (Hsu et al. 2017). Similarly nano-biosensors are an advanced eco-friendly wing of the nano-sensors, as they include a biological organic moiety as a variant component in their formulation (Rai et al. 2012). In a more simple way it can be said that these nano-biosensors are equipped with utilitarian bio-components such as enzymes, proteins and nucleic acids, which could be perceptible via diversified means within plants (Misra et al. 2013). Da Silva et al. (2013) demonstrated for the first time the implementation of atomic force spectroscopy in the detection of enzyme-inhibiting herbicides. They developed and characterized a nano-biosensor based on atomic force microscopy tip functionalized with acetolactate synthase enzyme which was used for detection of an herbicide metsulfuron-methyl. Nano-biosensors are a growing technology of for simple, sensitive, selective, and rapid detection methods and with the present circumstances it could be speculated that one day this multidisciplinary piece of technology will certainly change the course of history.

1.2.4.2 Application in Crop Improvement

Crop improvement is the primary task of any agricultural inputs which also shows significant and promising results. This has also been achieved using nanotechnology, where enhanced sensing technologies through nano-sensors/ nano-biosensors, have up regulated the management and conservation of input in crops in the current agricultural practices. In present situation, the foremost limiting factor for crop improvement includes biotic and abiotic stress or the combined stress which adversely affects the productivity of the plant (Singh et al. 2016; Pandey et al. 2017). The biotic stress encompasses different plant disease due to viruses, bacteria and funguses and secondly the abiotic stress, which is mainly due to up or down regulation of certain protein or growth factors, again the min influencer for which are temperature, pressure, pH, moisture content, imbalance in ion and nutrient concentration (Pandey et al. 2017). In the present century, the population explosion has laid to uncontrolled pollution of air, water and land has enhanced the destabilization of the abiotic factors resulting in increased stress (Crippa et al. 2016). Moreover, the stingy nature of mankind has laid the founding for unethical experimentation which resulted in origin of new genetically modified resistance organisms causing unprecedented diseases in both plants and animals (Maghari and Ardekani 2011).

Precocious detection of plant disease ahead of time has impelled present researchers to look for nanotechnology based remedies for crop plants against biotic stress through the utilization of autarchic nano-sensors which are linked to GPS system for real time monitoring the status or the condition of the soil and the crops (Misra et al. 2013). DNA detection is one of the basic research methods that have been widely exploited science the beginning. Despite that, it is still a sophistication to detect unambiguous sequence of DNA or low abundance genes in biological sample with specificity and sensitivity. Recently surface enhanced Raman scattering (SERS) technology based bio-sensing platform has been studied. Here a target DNA (tDNA) accelerates self-orientation of gold nanoparticles (AuNPs) probes on DNA which is in the form of nanowires for signal amplification in DNA detection based on hybridization chain reaction. This technique can be used for any biological sample (Chen et al. 2014). Optical nano-biosensors based on fluorescence resonance energy transfer (FRET) have been studied by Bagheri et al. (2017) where they detected tropane alkaloids as anti-cholinergic agents in both natural and transgenic hairy root extract of *Atropa belladonna*. They formulated a sensor of cadmium telluride quantum dots with M2 muscarinic receptor and tioglycoyic acid as capping agent along with scopolamine-rhodamine 123 conjugate.

Abiotic stress on the other hand is another speed breaker that hinders the progressivity of sustainable crop improvement. Nutritional scarcity and heavy metal accumulation leading to generation of ROS which further results in senescence, must be detected at an early stage (Meena et al. 2017). The task which has been achieved to a greater extent by nano-sensors is the primary consideration of present research (Zaytseva and Neumann 2016). Taher et al. had developed a new solid-phase extraction method using oxidized multiwalled carbon nanotubes in concentrated HNO_3 which was again modified with 2-(5-bromo-2-pyridylazo)-5-diethylaminophenol for extraction, pre-concentration, and electrothermal atomic absorption spectrometric determination in real sample which were at ng/L level (Taher et al. 2014). Choi and Gilroy (2014) developed Fluorescence Resonance Energy Transfer (FRET) based biosensor to report the level of stress hormone specifically abscisic acid within the plant cell of *Arabidopsis thaliana* in real-time. Sooner or later the nanoform of this biosensor will be developed and during that time no stones will be left unturned.

1.2.5 Genetic Manipulation of Crop Plants through Nano-Devices for Disease Diagnosis and Improvement

Genetic manipulation of plants means modification of the chromosomal or extra chromosomal DNA directly or indirectly, which leads to the formation of genetically modified organisms (GMOs) or genetically modified plants or crops (Zhang et al. 2016). Since 1859, when Charles Darwin published the first edition of “On the Origin of Species” till now when Nanocarriers for carrying desired gene to the preferred site with efficiency and controlled release, the research is constantly booming (Zhang et al. 2016; Wu et al. 2017). But the beginning was always humble in case of its application for the razing poverty. One of the finest pioneered works in this sector is “Golden rice” that had been designed to express high level of beta-carotene or a cost-effective and efficient way to deliverer dietary source of Vitamin A (Oliver 2014). Plants resistance against various parasites was developed and adapted that had previously been modified through genetic engineering conjugated with nanotechnology. In some studies biological pesticides like abamectin (Abm) which has been modified through nanotechnology and genetic manipulation to improve its poor mobility and nematicidic activity that was previously due to restricted area of protection around the developing root system. Technically Abm’s physical chemistry was manipulated by encapsulating it with *Red clover necrotic mosaic virus* (RCNMV) that resulted in the formation of an efficient plant virus nanoparticles (PNV) delivery system (Cao et al. 2015).

Nutrient deficiency is another important problem that has been easily mitigated by use of nanocarriers that directly fulfills the requirement of plant nutrient requirement. One such study was conducted on cereals in zinc deficient soil where the deficiency of the micronutrient was ameliorated by the application of nanotechnology. Here zinc deficiency in the cereal grains were enhanced by zinc complexes chitosan nanoparticles which was synthesized by using tri-polyphosphate as cross-linker (Deshpande et al. 2017). Crop quality can be further improved by local translocation of small RNAs between cells. This phenomenon has been experimented in tomato which was grafted into goji (*Lycium chinense*) that reveals the hidden activity of miRNAs in regulation and expression arrangements within a distance grafting system (Khaldun et al. 2016). The point where nanotechnology meets plant biotechnology is like science-fiction meeting reality, where nanocarriers are used in gene delivery to plant cells. Nanocarriers such as carbon nanotubes immobilized with cellulase had been studied for its ability to deliver DNA effectively (Fouad et al. 2008). One of the important biomedical systems, named calcium phosphate (CaP) having diversified application including delivering plasmid DNA, is a widely used non-viral gene delivery method. The efficiency of CaP nanoparticles in delivering pBI121 harboring GFP by 35S promoter-encoding plasmid DNA into tobacco cells have been evaluated (Ardekani et al. 2014). Currently the application only involves the delivery of bioactive compounds such as proteins and genetic materials or certain drugs to the animal cells. Again there is a long way to go in the path where nanodevices will be efficiently used for the delivery of genetic material to plant cells (Menaa 2015).

1.2.6 Nanocomposites/Nano-Biocomposites in Agricultural Development

A nanocomposite is a multiphase solid material with a dimension of less than 100 nm composed of nano-sized ceramics or other natomaterials either organic or inorganic with a capacity of substantially enhancing the composite property of the matter containing these nanocomposites (Bogue 2011; Barahuie et al. 2013). Unlike nanocomposites, polymeric nanocomposites are intensely cross-linked, that gives rise to the exquisite properties characteristically high stiffness, strength, creep, chemical corrosion resistance and elevated temperature tolerability. Further the polymer nanocomposite property depends upon diversified parameters such as shape, adhesive natures and dispersive phase (Puggal et al. 2016). Polymers shows better biocompatibility properties when they are of biological origin such as proteins/ enzymes that have excellent electro catalytic activity. The activity which is a result of charge distribution within the inter or intra molecular residues of the protein which together with the matrix gives rise to a versatile form of biocompatible nanocomposites with indefinite possibilities (Jamir and Mahato 2016).

These nanocomposites/nanobiocomposites are currently being exploited for the development in agricultural activity in a diversified way directly or indirectly. Though there has not yet been any direct study on how nanocomposites effect or interact with crops, but it can be assumed that the side effect is negligible because every risk in science is stepping forward in the path of enlightenment in knowledge of understanding the scientific phenomenon little bit closer. Presently the application of nanocomposites is focused or in other words it can also be said that it is limited only to certain application like food packaging, preservation, restoration of dynamic property of soil and/ or nano-biofertilizers, biosensors/ nano-biosensors (Sekhon 2014). A report proves the development of efficient bioactive packaging by nutraceuticals inspired pectin- magnesium hydroxide (Mg $(OH)_2$) nanocomposites. Here a bioactive edible film based on pectin was developed as a dietary scaffold and nanoplates of Mg $(OH)_2$ as the reinforcing filler. The nanocomposite morphological characterization was carried out with the help of atomic force microscopy and Fourier transform infrared spectroscopy (Moreira et al. 2013). Food preservation could be effectively enhanced by nanocomposite synthesized from chitosan, nano-cellulose fiber and thyme oils.

The nanocomposite affected the moisture content of the preserved fruits which was further followed by decrement in weight and total sugar content, while acidity was unaltered. Overall it can be said that the coating with nanocomposite leads to increased shelf life and reduction in fungal growth (Nabifarkhani et al. 2015). Soil is the most vital component of the sustainable agriculture and therefore conserving its dynamic nature in itself is a great task. Though presently fertilizers are been used for maintaining its stability, its adverse effect is unavoidable. Therefore, nanofertilizers are the current applied techniques to reduce the adverse effect of the fertilizers. One of such study is being done by using nanocomposite for improving phosphate and urea intake of the soil. The nanocomposite was prepared from urea or extruded thermoplastic starch/ urea medleys as a matrix with hydroxyapatite (Giroto et al. 2017). There are many other application such as nano-clay, biochar-nanoparticle as nanocomposite and many other polymer based nanocomposite that have already being used for the development of agriculture but only at experimental level. The present effort should be to bring these versatile magnificent technologies out in to the field to each and every farmer so that the productivity would never cease.

1.2.7 Application of Nanotechnology in Hydroponic

Hydroponics is a precocious technology where plants were artificially grown in a liquid solution containing all of the required nutrients. This marvelous technology named hydroponic system is in extensive use in the present decade to study and understand the biotic and abiotic stress response to plant (Nguyen et al. 2016). Now a days in supermarkets the displayed fruits and vegetables are grown hydroponically of which the most common crops are tomatoes, cucumbers, sweet peppers, melons, lettuce, strawberries, herbs, eggplant, and chilies (Sekhon 2014). This technique was actually able to accelerate the kinetics of growth in the plant with respect to time that the plant normally required for its growth. The phenomenon was studied successfully in the Electro-Hydroponic culture system where the application of an electric field with varying intensity of direct current at galvanostatic regime (50–12.5 mA) along with required nutrient solution for the effective, alternative and interesting harvest technique for the growth of *Lactuca sativa* (Fuentes-Castaneda et al. 2016). The technique can further be advanced with the help of nanotechnology by the implementation of nano-pesticides which is sometimes a necessary, nanofilters, nano-preservatives for maintenance of the adequate moisture content of seeds. Currently nano bubbles play a major role in the process of seed germination which is again a vital step for plant development. These nano bubbles ultimately help to hydrate the seedling and improve its metabolism and ultimately their growth enhancement.

This prepares a wider sphere for growth of hydroponic plants and hence, improves agro ecosystem. This whole process takes place by increasing the OH^- concentration in the water which forms shells and hence, no space for further gas dissolution (Ushikubo et al. 2010). Again these nano-bubbles generally increase the oxygen concentration in the air nano bubble reactor. In a study conducted for time duration of 4 weeks, on hydroponic growth of *Brassica campestris* shows that nano-bubble has a great impact on the co-cultured organisms like fishes. An air nano-bubble reactor which continuously releases air nano bubbles improves the growth of sweet fishes and rainbow trout. Nano air bubbles for 3 weeks in case of sweet fishes and 4 weeks in case of rainbow trout is shows better growth (Ebina et al. 2013).The impact of titanium dioxide nanoparticles (TiO_2 NPs) on growth and survival of the nitrogen fixing bacterium *Rhizobium trifolii* in the symbiotic root nodule of the plant *Trifolium pretense* along with the growth of the plant in the hydroponic system was investigated through eco-toxicological tests. The results indicated that about 21% of the TiO_2 NPs treated plants were devoid of the nodulation and at elevated concentration of NPs resulted in the impaired *R. trifolii* as well as the growth of *T. pretense* plant (Moll et al. 2016). Nanotechnology in these ways could reduce the energy requirements, time and overall cost and soil exploitation and pave a path for sustainable agriculture.

1.2.8 Application of Nanotechnology in Organic Agriculture

The biological or ecological agriculture in conjugation with classical feasible farming methods with advanced sustainable farming technology which is commonly known as organic agriculture is one of the preferred nutrient source. It focuses mainly on rotating crops, natural management of pests, variation in crops, diversity in livestock, and conservation and maintenance of soil quality along the addition of compost and green manures (Reganold and Wachter 2016). Organic agriculture enhances the health of agro-ecosystem in diversified ways and means. Now, incorporating nanotechnology to it would not only improve the quality of crops but also give a boost to the livestock. Several companies are predicting that the application of nanotechnology would uplift the economy of food industry and hence, termed as ‘agrifood nanotechnology’. Firstly, nanotechnology is applied to the food and animal feed in form of colouring, vitamins, or flavours within nanocapsules. Secondly, nanotechnology has applications in fertilizers which lessen its utility in crops (Jahanban and Davari 2014). At present nanoparticles are used in animal feeds as colouring, flavours and nutrition/ vitamins in the form of nanocapsules, which because of nano size could able to dissolve readily and efficiently in beverages (Huang et al. 2015). Moreover nano-formulations of fertilizers of biotic origin shows more efficiency in comparison to conventional fertilizers and lastly biopolymers with integrated nanoparticles proves to be compostable and more kinetically stable than other biopolymers (Jahanban and Davari 2014). As International Federation on Organic Agriculture Movements (IFOAM) had rejected the use of nanotechnology and nanomaterials in organic agriculture, therefore research regarding the use of nanoparticles in organic agriculture is somewhat limited (Sekhon 2014).

1.3 Application of Nanotechnology in Poultry and Animal Health

It was previously known that nanotechnology is venturing in every field of science and research and leaving behind spectacular trails of new scientific possibilities. These new panoramas of nanotechnology in combination with other derived fields of science such as molecular biology, animal biotechnology and to some extent clinical biotechnology have invigorated nearly every sector of veterinary and animal sciences by stunningly modulating the synergetic applications in relation to sustainable poultry production (Muktar et al. 2015). There are discrete forms of nanomaterials that could be effectively used for disease diagnosis, treatment, supplementation in animal nutrition, efficient animal breeding, safe reproduction, and value-added poultry products (Thornton 2010). Some of the commonly used nanomaterials includes metallic nanoparticles, quantum dots, single walled and multi-walled carbon nanotubes, fullerenes, liposomes and dendrimers (Sekhon 2014). Despite the serviceability of nanotechnology and its exploitations in major innovations, it is still developing and assumed to hinder environment and its components directly or indirectly. Hence, the research of the present decade is more concerned to develop nanomaterial with ameliorated toxicity and spread awareness of the benefits as well as potential risk (Thornton 2010).

Nutrition delivery is the primary concern of any livestock industry and nanotechnology is slowly advancing in the concern sector. A study was conducted to evaluate the impact of different level of nano chromium picolinate (nanoCrPic) on egg quality, mineral retention and mineral accumulation within the tissue of chickens. It was found that the supplemental nano CrPic could effectively enhance egg quality, withholding of chromium and zinc ions, and increased concentration of mineral accumulation in the liver (Cr, Ca, P) and yolk (Ca), and in eggshell (Ca) (Sirirat et al. 2013). Nano-polymers in conjugation to nutrients could be highly efficient for delivery to the gastrointestinal compartment. Because it is evident from previous studies that the nanoparticle with their versatile morphological, physical and chemical properties could easily overcome the extreme alkaline and acidic condition of the gut (Ban et al. 2015). Biocidic applicability could be easily attained by fabricating magnetic nanoparticles around gold nanoparticles by means of photothermal lysis of photogenic bacterium *Salmonella typhi* is one of the growing technique is investigated by the researchers all over the world. It is a simple technique where after the absorption of light by the nanohybrid, it from its electromagnetic energy conversion generates heat in the surrounding medium that quickly shifts the temperature to an intolerable extent for the pathogen and results in their lysis (Ramasamy et al. 2016).

Detection and diagnosis through luminescence is an expanding field of medical science. Presently real-time imaging by a probe, named ratiometric mitochondrial cysteine-selective two-photon fluorescence was developed by using the biothiol reaction site of acrylate moiety and a merocyanine as a fluorophore is widely studied for their applicability in diagnostics (Niu et al. 2016). Nanoparticle-based antibodies or lectins can be used as surface markers for the removal of aberrant spermatozoa. A study conducted on the ability to remove defective spermatozoa by nanoparticle-based magnetic purification method from bull semen was proven to be efficient in improving sperm sample viability, fertilizing ability both *in vitro* and *in vivo*. The two types of nanoparticles used in the present research include an antibody against ubiquitin and another nanoparticle coated with lectin PNA. No side effect was observed in all of the 466 healthy inseminated animals or their offspring (Odhiambo et al. 2014). Nanocarrier mediated delivery, on the other hand, is another fast growing and promising technique in reproductive biology because of the potentiality in the improvement of the safety and efficiency of existing methodologies that includes *in vitro* and *in vivo* experimental gene therapy and sperm-mediated gene transfer. A pioneering study on the use of mesoporous silica nanoparticles with the symmetry of the pores that were hexagonal in structure and surface functionalized with polyethileneimine and aminopropyltriethoxysilane and facultatively packed with two common types of bioactive compounds such as nucleic acid or proteins for intact association with sperm without showing any negative effect upon the primary parameters of sperm functions (Barkalina et al. 2014). Nanoparticles are commercialized and their development is in continues progression, their spectacular properties are being manipulated and optimized on the basis of particular function in which they could be used, but still then in the case of animal production nanotechnology is still in its infancy in certain applications (Hill and Li 2017).

1.4 Application of Nanotechnology in Post-Harvest Management of Agricultural Goods

Fresh Fruits and Vegetables (FFV) are the imperative origins of vital vitamins such as vitamin A and C along with minerals like potassium and other ions for eudaimonia. The problem is that, these are perishable living products that required an extra coordinated attention by the producers after harvest, but due to unawareness of proper consideration of the necessity condition results in the loss of harvested FFVs unexpectedly (Mahajan et al. 2014).Post-harvest management refers to mitigate the unexpected measurable loss of both quality and quantity of harvested food crops in storage, packaging, transportation, processing and appropriate preparation before consumption. Paucity in appropriate skill and technology post-harvest management such as maintenance of the optimum temperature for longer time period without the loss of important nutritional values and proper packaging techniques to avoid several unexpected short comings that might hamper the food security that has already caused alarming threat of high level of poverty among the developing countries (James and Zikankuba 2017). Classical management system is inefficient in maintaining all the adequate condition simultaneously because of high energy cost of both labor and equipment and scaling up of the products, deficiency of edible materials with required properties, intensive investment, autonomous harmonized regulatory jurisdiction or laws, sluggish consumer acceptance owing to noticed alliance with radioactivity, difficulty to reach unreachable sites for treatment of fresh products within calyx and wax areas and elevated concentration of the chemical agents used may induce health hazards (Mahajan et al. 2014).

In the present scenario, some of these drawbacks could be alleviated by the application of nanotechnology. Currently modulating the growth and development of microorganisms by the use nanomaterials like graphene oxide that is in the form of nanosheet, generation of efficient packaging covers or films made up of nano-objects like nanorods, nanotubes, and nanowires that can also be called as nanofiber are slowly commercializing because of their inhibiting the entry of gases and the harmful rays (Palmieri et al. 2017; Wyser et al. 2016). Strength, quality and the morphological beauty of the packaging material is also further advanced by the application of nanotechnology (Pradhan et al. 2015). Further nano-biosensors are used for labeling products and are considered as the primary step in an automatically controlled storage (Ali et al. 2017). In this way the application of nanotechnology in the processes of altering the sophistications that previously were limiting developments in the field of effectively of the post-harvest management.

1.5 Conclusion and Future Prospects

Future could be alarming, but it is this fear that propels the mankind to constantly focus on eradicating or mitigating the possible expected cause that might ignite such alarming effect. Researchers are increasingly, trying to unfold the vast mysteries which are seemingly hidden in the earth as well as in the distant stars within visible universe as well as beyond it in the near future. The more mankind enlightens themselves with the understanding of the nature, the greater will be the understanding of our insignificant character. Humans have much to learn and much to understand from this unexplored and unique universe as well as from ourselves and our needs. As mankind is the present known smartest creature of the earth, the responsibilities in conserving the nature should be also done in a smarter way. But instead exploitation of the dispensable values of the Mother Nature is currently on the verge of extinction. Still there is hope. An antidote which we call as science is referred to as good servant but bad master. Present unsustainable harvest technique demands for more developed ways and means to combat or tackle the upcoming wave of poverty that might one day take over the world. Some of the future technique that might be a silver lining for agricultural development includes the following;

The indispensable abiotic yet dynamic component of agriculture is soil, which is slowly losing its dynamic properties, but could be restored efficiently by the application of nanotechnology (Malik and Kumar 2014). Nano-biosensors are currently a simple but effective way of detecting the deficiency in the soil by colour, light and heat (Wang et al. 2016). After detection the next task is the neutralization of the problem that too is possible with the help of nanotechnology. Basing the specific type of deficiency of the soil, nanocarriers could be developed which could effectively deliver the required supplement of the soil (Malik and Kumar 2014; Deshpande et al. 2017). Once the soil is enriched, plants are the vital component to which the focus shifts. The linked problems include insects and parasites that could also be more efficiently dealt with the application of nano-pesticides, nano-insecticides, nano-fungicides etc. (Yearla and Padmasree 2016). Further, genetic engineered crop plants could be developed by the application of molecular biology in combination with nanocarriers could result in the development of disease resistance plants, plants with essential vitamins, proteins, hormones etc. (Ardekani et al. 2014; Oliver 2014; Zhang et al. 2016; Wu et al. 2017). Lastly effectual mode of management of the agricultural products till it reach the end user is a very important task. Therefore promising measures should be taken to manage these products for which competent mode of preservation, packaging, transport and delivery is required. Nanotechnology could further used for the improvement of the post-harvest management of the agricultural goods (Palmieri et al. 2017; Wyser et al. 2016). Apart from these applications nanotechnology have touched every aspect of sustainable agricultural development in the present as well as the future. It is not late when nanotechnology will be regarded as the central axis in overthrowing the poverty through its application in sustainable agricultural development in the current century.

Acknowledgements Authors are grateful to Dr. Leonardo F. Fraceto of Department of Environmental Engineering, São Paulo State University, Sorocaba, Brazil for giving permission to include their Fig. 1.1 (as Fig. 1.2) and to Dr. Claudia Parisi of European Commission, Joint Research Centre (JRC), Institute for Prospective Technological Studies (IPTS), Edificio Expo, C/ Inca Garcilaso3, 41,092 Seville, Spain for giving permission to include their table (as Table 1.2) in the current chapter. We are also grateful to Frontiers in Environmental Science and Nano Today journal for permission to include the figure and table under creative commons open access licence.

References

Adak T, Kumar J, Shakil NA, Walia S (2012) Development of controlled release formulations of imidacloprid employing novel nano-ranged amphiphilic polymers. J Environ Sci Health B 47(3):217–225

Alemdar A, Sain M (2008) Isolation and characterization of nanofibers from agricultural residues: wheat straw and soy hulls. Bioresour Technol 99(6):1664–1671

Ali J, Najeeb J, Ali MA, Aslam MF, Raza A (2017) Biosensors: their fundamentals, designs, types and most recent impactful applications: a review. J Biosens Bioelectron 8:1
Anjali CH, Sharma Y, Mukherjee A, Chandrasekaran N (2012) Neem oil (*Azadirachta indica*) nanoemulsion--a potent larvicidal agent against *Culex quinquefasciatus*. Pest Manag Sci 68(2):158–163
Ardekani MRS, Abdin MZ, Nasrullah N, Samim M (2014) Calcium phosphate nanoparticles a novel non-viral gene delivery system for genetic transformation of tobacco. Int J Pharm Pharm Sci 6(6):605–609
Arlett JL, Myers EB, Roukes ML (2011) Comparative advantages of mechanical biosensors. Nat Nanotechnol 6:203–215
Bagheri F, Piri K, Mohsenifar A, Ghaderi S (2017) FRET-based nanobiosensor for detection of scopolamine in hairy root extraction of *Atropa belladonna*. Talanta 164:593–600
Ban C, Park SJ, Lim S et al (2015) Improving flavonoid bioaccessibility using an edible oil-based lipid nanoparticle for oral delivery. J Agric Food Chem 63:5266–5272
Barahuie F, Hussein MZ, Hussein-Al-Ali SH et al (2013) Preparation and controlled-release studies of a protocatechuic acid-magnesium/aluminum-layered double hydroxide nanocomposite. Int J Nanomedicine 8:1975–1987
Barkalina N, Jones C, Kashir J et al (2014) Effects of mesoporous silica nanoparticles upon the function of mammalian sperm *in vitro*. Nanomedicine 10:859–870
Benzon HRL, Rubenecia MRU, Ultra VU Jr, Lee SC (2015) Nano-fertilizer affects the growth, development, and chemical properties of rice. Int J Agric Res 7(1):105–117
Bhandari G (2014) An overview of agrochemicals and their effects on environment in Nepal. Appl Ecol Environ Sci 2(2):66–73
Boehm AL, Martinon I, Zerrouk R et al (2003) Nanoprecipitation technique for the encapsulation of agrochemical active ingredients. J Microencapsul 20(4):433–441
Bogue R (2011) Nanocomposites: a review of technology and applications. Assem Autom 31:106–112
Bulbul G, Hayat A, Andreescu S (2015) Portable nanoparticle-based sensors for food safety assessment. Sensors (Basel) 15(12):30736–30758
Cao J, Guenther RH, Sit TL et al (2015) Development of abamectin loaded plant virus nanoparticles for efficacious plant parasitic nematode control. ACS Appl Mater Interfaces 7(18):9546–9553
Cao L, Zhang H, Cao C et al (2016) Quaternized chitosan-capped mesoporous silica nanoparticles as nanocarriers for controlled pesticide release. Nanomaterials (Basel) 6(7):126
Chang YC, Lin YS, Xiao GT et al (2016) A highly selective and sensitive nanosensor for the detection of glyphosate. Talanta 161:94–98
Chauhan N, Gopal DM, Kumar R, Kim K-H, Kumar S (2016) Development of chitosan nanocapsules for the controlled release of hexaconazole. Int J Biol Macromol 97:616–624
Chen K, Wu L, Jiang X et al (2014) Target triggered self-assembly of Au nanoparticles for amplified detection of *Bacillus thuringiensis* transgenic sequence using SERS. Biosens Bioelect 62:196–200
Chen G, Qiu J, Liu Y et al (2015) Carbon nanotubes act as contaminant carriers and translocate within plants. Sci Rep 2015(5):15682
Cheng HN, Klasson KT, Asakura T, Wu Q (2016) Nanotechnology in agriculture. In: Cheng HN, Doemeny L, Geraci CL, Schmidt DG (eds) Nanotechnology: delivering on the promise, vol 2, ACS symposium series, vol 1224. American Chemical Society, Washington, DC, pp 233–242
Choi WG, Gilroy S (2014) Plant biologists FRET over stress. eLife 3:e02763
Cortesi R, Valacchi G, Muresan X-M et al (2017) Nanostructured lipid carriers (NLC) for the delivery of natural molecules with antimicrobial activity: production, characterization and in vitro studies. J Microencapsul 34:63–72
Crippa P, Castruccio S, Archer-Nicholls S et al (2016) Population exposure to hazardous air quality due to the 2015 fires in Equatorial Asia. Sci Rep 6(37074):1–9
Da Silva ACN, Deda DK, Da Roz AL et al (2013) Nanobiosensors based on chemically modified *afm* probes: a useful tool for metsulfuron-methyl detection. Sensors 13:1477–1489

Deshpande P, Dapkekar A, Oak MD et al (2017) Zinc complexed chitosan/TPP nanoparticles: a promising micronutrient nanocarrier suited for foliar application. Carbohydr Polym 165:394–401

Ebina K, Shi K, Hirao M et al (2013) Oxygen and air Nanobubble water solution promote the growth of plants, fishes, and mice. PLoS One 8(6):e65339

FAO (2017) The future of food and agriculture – trends and challenges, Rome

FDA (2005) Glossary of pesticide chemicals. http://www.fda.gov/

FDA (2014) Pesticide residue monitoring program fiscal year report. https://www.fda.gov/downloads/Food/.../Pesticides/UCM546325

Fouad M, Kaji N, Jabasini M et al (2008) Nanotechnology meets plant biotechnology: carbon nanotubes deliver DNA and incorporate into the plant cell structure, 12th international conference on miniaturized systems for chemistry and life sciences, 2008, San Diego, CA, USA

Fraceto LF, Grillo R, de Medeiros GA et al (2016) Nanotechnology in agriculture: which innovation potential does it have? Front Environ Sci 4(20). https://doi.org/10.3389/fenvs.2016.00020.

Fuentes-Castaneda O, Dominguez-Patiño ML, Dominguez-Patino J et al (2016) Effect of electric field on the kinetics of growth of lettuce (*Lactuca sativa*) in a hydroponic system. J Agric Chem Environ 5:113–120

Giroto AS, Guimaraes GGF, Foschini M, Ribeiro C (2017) Role of slow-release nanocomposite fertilizers on nitrogen and phosphate availability in soil. Sci Rep 7(46032):1–11

González-Melendi P, Fernandez-Pacheco R, Coronado MJ et al (2008) Nanoparticles as smart treatment-delivery systems in plants: assessment of different techniques of microscopy for their visualization in plant tissues. Ann Bot 101(1):187–195

Gul HT, Saeed S, Khan FZA, Manzoor SA (2014) Potential of nanotechnology in agriculture and crop protection: a review. Appl Sci Bus Econ 1(2):23–28

Hill EK, Li J (2017) Current and future prospects for nanotechnology in animal production. J Anim Sci Biotechnol 8:26

Hsu CW, Lin ZY, Chan TY et al (2017) Oxidized multiwalled carbon nanotubes decorated with silver nanoparticles for fluorometric detection of dimethoate. Food Chem 224:353–358

Huang S, Wang L, Liu L et al (2015) Nanotechnology in agriculture, livestock, and aquaculture in China: a review. Agron Sustain Dev 35:369–400

Husen A, Siddiqi KS (2014) Carbon and fullerene nanomaterials in plant system. J Nanobiotechnol 12:16

Jahanban L, Davari M (2014) Organic agriculture and nanotechnology. In: Rahmann G, Aksoy U (eds.) Proceedings of the 4th ISOFAR scientific conference. 'Building Organic Bridges', at the Organic World Congress, Istanbul, Turkey

James A, Zikankuba V (2017) Post harvest management of fruits and vegetable: a potential for reducing poverty, hidden hunger and malnutrition in sub-Sahara Africa. Cogent Food Agric 3:1312052

Jamir A, Mahato M (2016) A review on protein based nanobiocomposite for biosensor application. Rev Adv Sci Eng 5:109–122

Kah M, Weniger AK, Hofmann T (2016) Impacts of (nano) formulations on the fate of an insecticide in soil and consequences for environmental exposure assessment. Environ Sci Technol 50:10960–10967

Khaldun BM, Huang W, Haiyan L et al (2016) Comparative profiling of miRNAs and target gene identification in distant-grafting between tomato and *Lycium* (Goji Berry). Front Plant Sci 7(1475):1–18

Khati P, Chaudhary P, Gangola S, Bhatt P, Sharma A (2017) Nanochitosan supports growth of *Zea mays* and also maintains soil health following growth. 3 Biotech 7(1):81

Khiyami MA, Almoammar H, Awad YM et al (2014) Plant pathogen nanodiagnostic techniques: forthcoming changes? Biotechnol Biotechnol Equip 28(5):775–785

Khot LR, Sankaran S, Maja JM et al (2012) Applications of nanomaterials in agricultural production and crop protection: a review. Crop Prot 35:64–70

Lamsal K, Kim SW, Jung JH et al (2011) Application of silver nanoparticles for the control of Colletotrichum species *in vitro* and pepper anthracnose disease in field. Mycobiology 39(3):194–199

Lau HY, Wu H, Wee EJH et al (2017) Specific and sensitive isothermal electrochemical biosensor for plant pathogen DNA detection with colloidal gold nanoparticles as probes. Sci Rep 7:38896

Lima R, Feitosa LO, Maruyama CR et al (2012) Evaluation of the genotoxicity of cellulose nanofibers. Int J Nanomedicine 7:3555–3565

Lu CM, Zhang CY, Wen JQ et al (2002) Research of the effect of nanometer materials on germination and growth enhancement of *Glycine max* and its mechanism. Soybean Sci 21(3):168–171

Maghari BM, Ardekani AM (2011) Genetically modified foods and social concerns. Avicenna J Med Biotech 3(3):109–117

Mahajan PV, Caleb OJ, Singh Z, Watkins CB, Geyer M (2014) Postharvest treatments of fresh produce. Phil Trans R Soc A 372:20130309

Malik S, Kumar A (2014) Approach for nano-particle synthesis: using as nano-fertilizer. Int J Pharm Res Bio-Sci 3(3):519–527

McMurray TA, Dunlop PSM, Byrne JA (2006) The photocatalytic degradation of atrazine on nanoparticulate TiO2 films. J Photochem Photobiol A Chem 182:43–51

Meena KK, Sorty AM, Bitla UM et al (2017) Abiotic stress responses and microbe-mediated mitigation in plants: the omics strategies. Front Plant Sci 8(172):1–25

Menaa F (2015) Genetic engineering and nanotechnology: when science-fiction meets reality! Adv Genet Eng 4(2):1000128

Milani N, Hettiarachchi GM, Kirby JK et al (2015) Fate of zinc oxide nanoparticles coated onto macronutrient fertilizers in an alkaline calcareous soil. Plos One 10:e0126275. https://doi.org/10.1371/journal.pone.0126275

Misra AN, Misra M, Singh R (2013) Nanotechnology in agriculture and food industry. Int J Pure Appl Sci Technol 16(2):1–9

Mohammadi M, Pezeshki A, Abbasi MM et al (2017) Vitamin D3-loaded nanostructured lipid carriers as a potential approach for fortifying food beverages; in vitro and in vivo evaluation. Adv Pharm Bull 7(1):61–71

Moll J, Okupnik A, Gogos A et al (2016) Effects of titanium dioxide nanoparticles on red clover and its rhizobial symbiont. PLoS One 11(5):e0155111

Moreira FKV, Camargo LAD, Marconcini JM, Mattoso LHC (2013) Nutraceutically inspired pectin−$Mg(OH)_2$ nanocomposites for bioactive packaging applications. J Agric Food Chem 61:7110–7119

Muktar Y, Bikila T, Keffale M (2015) Application of nanotechnology for animal health and production improvement: a review. World Appl Sci J 33(10):1588–1596

Nabifarkhani N, Sharifani M, Garmakhany AD et al (2015) Effect of nano-composite and Thyme oil (*Tymus Vulgaris*) coating on fruit quality of sweet cherry (*Takdaneh* Cv) during storage period. Food Sci Nutr 3(4):349–354

Nagy L, Magyar M, Szabo T et al (2014) Photosynthetic machineries in nano-systems. Curr Protein Pept Sci 15(4):363–373

National Crime Records Bureau (NCRB) (2013) Accidental Deaths & Suicides in India (ADSI) annual reports. http://ncrb.nic.in/StatPublications/ADSI/PrevPublications.htm

National Crime Records Bureau (NCRB) (2014) Accidental Deaths & Suicides in India (ADSI) annual reports. http://ncrb.nic.in/StatPublications/ADSI/PrevPublications.htm

National Crime Records Bureau (NCRB) (2015) Accidental Deaths & Suicides in India (ADSI) annual reports. http://ncrb.nic.in/StatPublications/ADSI/ADSI2015/ADSI2015.asp

Nguyen NT, McInturf SA, Mendoza-Cózat DG (2016) Hydroponics: a versatile system to study nutrient allocation and plant responses to nutrient availability and exposure to toxic elements. J Vis Exp 113:e54317

Nhan LV, Ma C, Rui Y (2015) The effects of Fe_2O_3 nanoparticles on physiology and insecticide activity in non-transgenic and Bt-Transgenic cotton. Front Plant Sci 6:1263

Niu W, Guo L, Li Y et al (2016) Highly selective two-photon fluorescent probe for ratiometric sensing and imaging cysteine in mitochondria. Anal Chem 88(3):1908–1914

Odhiambo JF, DeJarnette JM, Geary TW et al (2014) Increased conception rates in beef cattle inseminated with nanopurified bull semen. Biol Reprod 91(4):97

Oliver MJ (2014) Why we need GMO crops in agriculture. Mo Med 111(6):492–507

Omanovic-Miklicanin E, Maksimovic M (2016) Nanosensors applications in agriculture and food industry. Bull Chem Technol Bosnia Herzegovina 47:59–70

Palmieri V, Bugli F, Lauriola MC et al (2017) Bacteria meet graphene: modulation of graphene oxide nanosheet interaction with human pathogens for effective antimicrobial therapy. ACS Biomater Sci Eng 3(4):619–627

Pandey P, Irulappan V, Bagavathiannan MV, Senthil-Kumar M (2017) Impact of combined abiotic and biotic stresses on plant growth and avenues for crop improvement by exploiting physio-morphological traits. Front Plant Sci 8(537):1–15

Parisi C, Vigani M, Rodriguez-Cerezo E (2015) Agricultural nanotechnologies: what are the current possibilities? Nano Today 10:124–127

Pereira MM, Mouton L, Yepremian C et al (2014) Ecotoxicological effects of carbon nanotubes and cellulose nanofibers in Chlorella vulgaris. J Nanobiotechnol 12:15

Pereira AES, Sandoval-Herrera IE, Zavala-Betancourt SA, Oliveira HC, Ledezma-Perez AS, Romero J, Fraceto LF (2016) Polyglutamic acid/chitosan nanoparticles for the plant growth regulator gibberellic acid: characterization and evaluation of biological activity. Carbohydr Polym 157:1862–1873

Poscic F, Mattiello A, Fellet G et al (2016) Effects of cerium and titanium oxide nanoparticles in soil on the nutrient composition of barley (*Hordeum vulgare* L.) Kernels. Int J Environ Res Public Health 13(6):577

Pradhan N, Singh S, Ojha N et al (2015) Facets of nanotechnology as seen in food processing, packaging, and preservation industry. Biomed Res Int 2015:1–17

Puggal S, Dhall N, Singh N, Litt MS (2016) A review on polymer nanocomposites: synthesis, characterization and mechanical properties. Indian J Sci Technol 9(4):1–6

Pyrgiotakis G, Vedantam P, Cirenza C et al (2016) Optimization of a nanotechnology based antimicrobial platform for food safety applications using engineered water nanostructures (EWNS). Sci Rep 6:21073

Rai V, Acharya S, Dey N (2012) Implications of nanobiosensors in agriculture. J Biomater Nanobiotechnol 3:315–324

Rajonee AA, Zaman S, Huq SMI (2017) Preparation, characterization and evaluation of efficacy of phosphorus and potassium incorporated nano fertilizer. Adv Nanopart 6:62–74

Ramasamy M, Kim S, Lee SS, Yi DK (2016) Recyclable photo-thermal nano-aggregates of magnetic nanoparticle conjugated gold nanorods for effective pathogenic bacteria lysis. J Nanosci Nanotechnol 16:555–561

Reganold JP, Wachter JM (2016) Organic agriculture in the twenty-first century. Nat Plants 2:1–8

Rui M, Ma C, Hao Y et al (2016) Iron oxide nanoparticles as a potential iron fertilizer for peanut (*Arachis hypogaea*). Front Plant Sci 7:815

Sabir S, Arshad A, Chaudhari SK (2014) Zinc oxide nanoparticles for revolutionizing agriculture: synthesis and applications. Sci World J 2014:925494

Schneider J, Börner D, Rosmalen PV, Specht M (2015) Augmenting the senses: a review on sensor-based learning support. Sensors 15:4097–4133

Sekhon BS (2014) Nanotechnology in agri-food production: an overview. Nanotechnol Sci Appl 7:31–53

Sekhon H, Ennew C, Kharouf H, Devlin J (2014) Trustworthiness and trust: influences and implications. J Mark Manage 30(3-4):409–430

Semo E, Kesselman ED, Livney DYD (2007) Casein micelle as a natural nano-capsular vehicle for nutraceuticals. Food Hydrocoll 21:936–942

Singh A, Singh S, Prasad SM (2016) Scope of nanotechnology in crop science: profit or loss. Res Rev J Bot Sci 5(1):1–4

Sirirat N, Lu JJ, Hung AT, Lien TF (2013) Effect of different levels of nanoparticles chromium picolinate supplementation on performance, egg quality, mineral retention, and tissues minerals accumulation in layer chickens. J Agric Sci 5:150–159

Srilatha B (2011) Nanotechnology in agriculture. J Nanomed Nanotechnol 2(123):7. https://doi.org/10.4172/2157-7439.1000123

Taher MA, Mazaheri L, Ashkenani H et al (2014) Determination of nickel in water, food, and biological samples by electrothermal atomic absorption spectrometry after preconcentration on modified carbon nanotubes. J AOAC Int 97:225–231

The World's Cities (2016) United Nations, Department of Economic and Social Affairs, Population Division. Data booklet (ST/ESA/ SER.A/392), pp 1–26

Thornton PK (2010) Livestock production: recent trends, future prospects. Philos Trans R Soc B 365:2853–2867

Torney F, Trewyn BG, Lin VS, Wang K (2007) Mesoporous silica nanoparticles deliver DNA and chemicals into plants. Nat Nanotechnol 2(5):295–300

Turner APF (2013) Biosensors: sense and sensibility. Chem Soc Rev 42:3184–3196

Ushikubo FY, Furukawa T, Nakagawa R et al (2010) Evidence of the existence and the stability of nano-bubbles in water. Colloids Surf A Physicochem Eng Asp 361:31–37

Vamvakaki V, Chaniotakis NA (2007) Pesticide detection with a liposome-based nano-biosensor. Biosens Bioelectron 22(12):2848–2853

Vasimalai N, John SA (2013) Biopolymer capped silver nanoparticles as fluorophore for ultrasensitive and selective determination of malathion. Talanta 115:24–31

Wang Y, Sun C, Zhao X et al (2016) The application of nano-TiO_2 photo semiconductors in agriculture. Nanoscale Res Lett 11:529

World Bank (2017) Enabling the business of agriculture. World Bank, Washington, DC. https://doi.org/10.1596/978-1-4648-1021-3

Wu Z, Xu XL, Zhang JZ et al (2017) Magnetic cationic amylose nanoparticles used to deliver survivin-small interfering RNA for gene therapy of hepatocellular carcinoma *in vitro*. Nanomat 7(110):1–13

Wyser Y, Adams M, Avella M et al (2016) Outlook and challenges of nanotechnologies for food packaging. Packag Technol Sci 29:615–648

Yearla SR, Padmasree K (2016) Exploitation of subabul stem lignin as a matrix in controlled release agrochemical nanoformulations: a case study with herbicide diuron. Environ Sci Pollut Res Int 23(18):18085–18098

Zaytseva O, Neumann G (2016) Carbon nanomaterials: production, impact on plant development, agricultural and environmental applications. Chem Biol Tech Agri 3(17):1–26

Zhang C, Wohlhueter R, Zhang H (2016) Genetically modified foods: a critical review of their promise and problems. Food Sci Human Wellness 5(3):116–123

Zhao L, Peng B, Hernandez-Viezcas JA et al (2012) Stress response and tolerance of *Zea mays* to CeO_2 nanoparticles: cross talk among H_2O_2, heat shock protein and lipid peroxidation. ACS Nano 6(11):9615–9622

Zhao L, Huang Y, Hannah-Bick C et al (2016) Application of metabolomics to assess the impact of $Cu(OH)_2$ nanopesticide on the nutritional value of lettuce (*Lactuca sativa*): enhanced Cu intake and reduced antioxidants. NanoImpact 3(4):58–66