Chapter 26
Nanobiotechnological Applications for Crop Improvement

Rachna Gupta and Parth Malik

Abstract Biotechnological solutions have revamped unpredictable agricultural vulnerabilities affecting the crop yield via numerous intricately woven mechanisms. Increasing population pressure and unregulated climate changes have been the major causes of mounting pressure on natural conditions. The depleting forest cover alongside deteriorating soil texture is the pivotal factor responsible for diminishing crop productivity and yield, forcing the pressure-ridden farmer to employ non-scientific curative measures with an expectation of improving crop harvest. Similarly, continuous planting of the same crop on a particular land area with unregulated pesticide and insecticide usage has depleted the nutrient content that has culminated into large areas of barren land. Biotechnological remedies offer valuable solutions to these multitude of risks, through practices such as crop rotation and newer automated irrigated methods. The emergence of nanotechnology principles has further consolidated the controlling grip of such biotechnological remedies. Recent studies have enabled numerous remedial recourses in this regard, with probe regulated pesticide distribution ensuring the prevention of arbitrary fertilizer loading on the soil. Prior testing of a pesticide formulation can provide adequate knowledge of its distribution potential, paving way for its uniform distribution across the entire vegetation area. Such interventions have not only reduced the chemical burden on soil but also reduced the usage of synthetic chemicals as fertilizers. On a similar basis, the feeding of nanotechnology-based foods to cattle has improved the manure quality and texture whereby betterment in existing crop yields is being exercised through simplistic environment-friendly procedures. With such insights, the present article sheds light on nanotechnology-based solutions to improve the agricultural output and quality.

Keywords Agricultural vulnerabilities · Biotechnology · Nanotechnology · Pesticide distribution · Pesticide formulation

---

R. Gupta
Department of Biotechnology, Visva-Bharati, Santiniketan, Bolpur, West Bengal, India

P. Malik (✉)
School of Nano Sciences, Central University of Gujarat, Gandhinagar, Gujarat, India

R. Roychowdhury et al. (eds.), *Sustainable Agriculture in the Era of Climate Change*, https://doi.org/10.1007/978-3-030-45669-6_26

1 Introduction

Agricultural activities and their financial contributions have always been at the central stage of the economic balance sheets amongst the different economies of the world. The dependence on agriculture is more significant for the rural population, where agricultural income is sometimes the sheer source of livelihood (Kydd 2002; Sharma 2015). With increasing population, the pressure on available resources, like functional cultivable area and the use of quality seeds, and the functional extent of fertilizers and pesticides have been increasing (Snodgrass and Wallace 1980; Mathur 1999). Consequently, a circumstantial necessity has made it mandatory to introduce technological breakthroughs for obtaining increasing outputs from the available land area. In the last 50 years, a number of technologies have been successfully integrated to uplift agricultural outputs from the economical as well as yield point of view (Kole et al. 1999; Keating et al. 2010; Mahadevan 2003). Though biotechnologies have always remained the forefront in this regard, a number of other sustainable measures have enabled a much better arrest of unpredictable scenarios. A major hurdle of conventional agricultural improvement measures is the controlling extent of their integrated application, such as the use of fertilizers and pesticides (including weedicides and insecticides) and regulating the dosage frequency at varying intervals of crop growth (Roychowdhury et al. 2013a, b). Though theoretical understanding of such probes creates reasonable reliability, the practical implementation remains a challenge as there are various factors which govern the accessible expressive mode of such measures. For example, the mere availability of a good pesticide (having broad functioning performance) is not sufficient since farmers with a lack of scientific understanding regarding its usage most likely encounter the menace of chemical clogging (Gupta et al. 1984; Forget 1993). This will not only result in economic loss to a farmer but will also mount the future uncertainties as the land area may become non-functional and viable for a long time. In such scenarios, it becomes dire essential to deliver the stimulators as and when required, in the needful proportions, and ensuring that a homogeneous distribution on the land area is available. To address such concerns, we need to have sharper tools with dual attributes of sensing and homogeneous delivery (Perlatti et al. 2013; Collins et al. 1973; Garrido-Herrera et al. 2009).

Apart from the above-mentioned aspects, a number of conventional techniques bring about the improvement through chemical actions whereby the deterioration risk of natural soil quality becomes high. So technologies need to be more biofriendly and eco-friendly which would enable the exercised remedial measures to manifest as habitual tendencies of the concerned land area. Such cautions would enhance the longevity of implemented solutions and will be a boost to naturally enhance the response, rather than only till the external monitoring. The emergence of nanoscale technologies has revolutionized the implementation of the multiplying tapping controls, substantially attributed to their precise control and regulating extents (Fig. 26.1). Amongst the several incentives, the foremost is the sensing advance where the levels of even till 10^{-12} units are now being

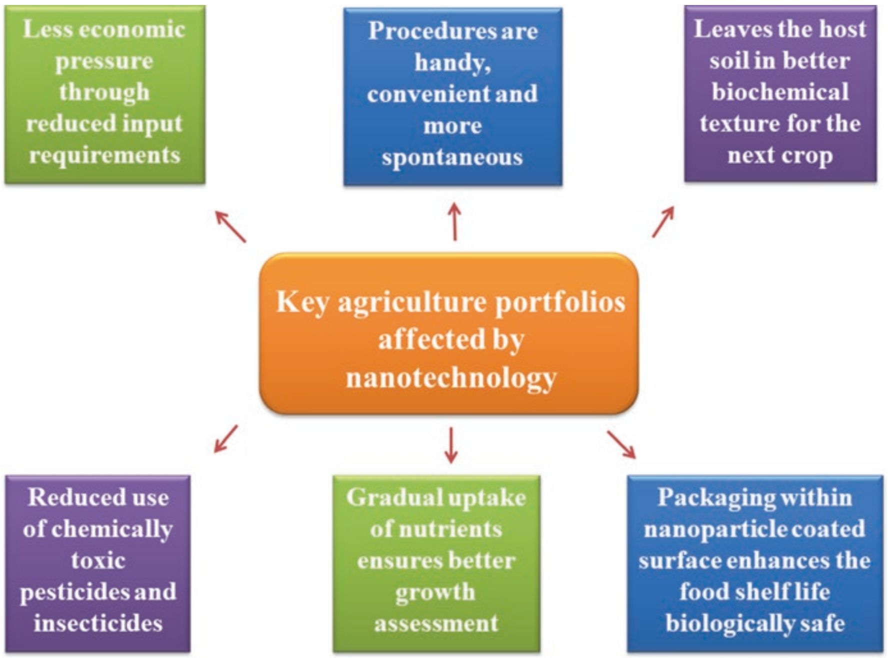

Fig. 26.1 The key agricultural activities that could be revolutionized using nanotechnological tools and techniques. Reduced material usage, quick detection of crop deteriorating pathogens and growth monitoring agents, with gradual fertilizer and pesticide delivery, are some of the crucial breakthroughs

estimated (Devreese 2007; Patolsky and Lieber 2005). Undoubtedly, the larger surface area of nanomaterials, particularly the various compatible nanoparticles (NPs) (prepared using non-chemical routes), makes it feasible to deliver simultaneous probes in the form of eco-friendly microbial species. For instance, the scenario where NPs and genetically modified organisms (suited to peculiar soil chemistry) are delivered together or feeding the crops with residual water streams whose chemical load is tolerable along with variable population of bioactive NPs could be the breakthrough solutions to augment the soil chemistry of a particular region (Oliver 2014).

Numerous NPs prepared from microbes are being used as catalysts to restore and increase the organic content in a particular soil area, which makes soil fit for all crops. The particular NPs used for this purpose include Au and Ag, owing to their least chemical reactivity along with the robust synthesis methods, requiring minimal chemical tediousness. Nanoscale probes have enabled contaminant detection even at the lowest possible levels so that the land area sustainability is not lost. Advanced measures of remote sensing (through geographical information systems [GIS]) have augmented the predictive assessments to select the suitability of a land area with respect to a specific crop. These advances are being used by developed economies to multiply their agricultural outputs with higher accuracy and in much lower times than conventional techniques. Similarly, the integration of nanotechnology to molecular biology techniques such as seed quality assessment and genetic testing has increased the reliability standards and reduced the vulnerabilities in the implemented solutions. Despite enormous potential, continuing research on agricultural nanotechnology over the past decade has left the scientific community amidst several tricky uncertainties. The clear-cut thrust areas where nanotechnology made its mark in the agricultural sector are increasing global food security and unpredictable climatic dilemmas. Till date, application of nanotechnology in agriculture has focused on reducing the use of deleterious chemicals, enhancing the yield through manipulated gene expression, improving the irrigation via homogeneous fertilizer and water distribution and better measures of soil quality improvement through live addition of nanoparticles forming genetically modified microbes (Maruyama et al. 2016). Though the commercial application of any major nanotechnology solution is still in the pipeline, the results of nanoscale control have been fabulous. This has not only reduced the intake of raw material but has also provided amicable solutions with reproducible and predictable benefits, in much lesser time, not to forget the incentive of allocating manpower to more serious issues, whereby sustainable income sources could be strengthened.

A wide range of agricultural products are already in the market and are booming well, particularly in the food and healthcare domain (Table 26.1) (the Project on Emerging Nanotechnologies (webpage); Huang 2012; Qureshi et al. 2012; Nanotechnology products and applications. Product: Guard IN Fresh. Honolulu, HI; Nanowerk; Nanotechnology products and applications. Product: NanoCeram-PAC. Honolulu, HI: Nanowerk; Miller and Senjen 2008; Hamad et al. 2018; Kalia and Parshad 2015). With such encouragements and multiple expectations, this chapter sheds light on the application of nanobiotechnological measures to the current agriculture techniques to improve the process as well as product quality.

2 Fascinations Behind the Expectations from Nanobiotechnology

Agricultural quality monitoring has been substantially dominated by biotechnological solutions till date, encompassing improvement in the seed quality, betterment in irrigation techniques and keeping the harvested crop in proper storage conditions before it is sent to the market. A lot has been made possible through controlled gene expression and exercising desired enzyme activity, which are the initial stages of any agricultural crop development process. The nanomaterials prove to have value-added benefits in this context, since their restricted dimensions (usually <500 nm) enable their robust accommodation so that larger functionalities could be integrated compared to conventional measures. Complementary to this size quality is the manifestation of quantum confinement effects, owing to which the salient material properties, ranging from optical, mechanical, electronic, chemical and electromechanical, are significantly altered. The foremost reason for such size dependent material

Table 26.1 An overview of nanotechnology-conceptualized commercial agriculture and food crop plants. The products offer numerous advantages, ranging from lesser input needed to controlling the delivery of the loaded active component

Product name	Marketed under	Specialty/purpose	Reference
Canola active oil	Shemen Industries, Tel Aviv, Israel	Comprises additive “nanodrops” optimized to transport vitamins, minerals and phytochemicals through the digestive system and urea	Project on Emerging Nanotechnologies (webpage), 2013
Nano tea	Qinhuangdao Taiji Ring Nano-Products Co., Ltd., Hebei, People’s Republic of China	Capable of releasing all tea essences, boosting the adsorption (adsorbing viruses, free radicals, cholesterol and blood fat) and annihilation of viruses through penetration	Huang (2012)
Nanoceuticals slim shake chocolate	RBC Life Sciences Inc., Irving, TX, USA	Comprises cocoa-infused “nanoclusters” to enhance taste and health benefits of cocoa without adding extra sugar	Qureshi et al. (2012)
Guard IN fresh	Fayetteville, AR, USA	Delays ripening of perishable foods and floral products through scavenging the ethylene gas	Nanotechnology products and applications. Product: Guard IN fresh, Honolulu, HI; Nanowerk, 2014
TopScreen DS13	TopChim, Wommelgem, Belgium	Recyclable water-based coating comprising of biopolymer facilitated monodispersed NPs to replace hard to recycle wax-based coatings and reduce any negative impact on food packaging biodegradability	Nanotechnology products and applications. Product: NanoCeram-PAC, Honolulu, HI; Nanowerk, 2014
NanoCeram-PAC	The Aquarian Environmental Group Pty Ltd., Sydney (Australia)	Substantial external surface area facilitates rapid absorption of soluble contaminants developing undesired taste and odour	Miller and Senjen (2008)
Food contact material	Nanosilver baby mug comprising of Ag NPs	Ag NPs confer better protection against bacterial contamination	Hamad et al. (2018) and Kalia and Parshad (2015)
Food packaging material	Durethan KU 2-2601 plastic wrapping, Bayer	Silica NPs embedded in a polymer-based nanocomposite prevent oxidative degradation of the product	Hamad et al. (2018) and Kalia and Parshad (2015)
Nutritional drink	Oat chocolate nutritional drink mix, toddler health, SunActive Fe	300 nm Fe particles ensure an improved bioavailability	Hamad et al. 2018 and Kalia and Parshad (2015)

properties is the closer spacing of discrete molecular energy levels as the dimensions progressively approach the nanoscale. Typically, this leaves us with the ultimate picture of having an exposed larger surface area, where multiple probes could be integrated. Such attributes confer multifunctional abilities to nanomaterials, making way for nanoparticle(s) conjugated with a dye, serving its native function as well as performing sensibly. So the foremost advantage of nanotechnology is the reduced material usage and the ability to perform multiple jobs with more precision than conventional materials. The next argument for preferential nanomaterial usage is the better integration of nanotechnology with several biotechnological practices being associated with agricultural output monitoring. For example, the use of enzyme-based sensors could be enhanced in its accuracy through the incorporation of metallic NPs, which would increase the precision limit and therefore make the detection more accurate. A detailed look on the diversity of differently abled nanobiosensors can be had in one of our earlier contributions (Malik et al. 2013). Similarly, fitting of nanoscale controllers along with dosage monitoring mechanisms could be exercised in conventional water and pesticide sprinklers, since the crops do not require the same input of water and pesticides in their entire growth process. Low toxicities of NPs alongside their robust synthesis routes from plants and even microbial species are the specialties for their robust implementation. For a detailed look of biological attributes of the plant and microbial synthesised NPs, readers are yet again advised to consult our earlier contributions (Malik et al. 2014; Gupta et al. 2019; Roy 2017). With such insights, the section ahead focuses on the recent progress in getting enhanced agricultural output through integrating applications of nanomaterials and nanodevices.

3 Recent Progress in Nanotechnology-Based Diversified Agricultural Betterments'

After the green revolution, there has not been any major technological intervention to uplift the agricultural outputs and the income generated thereof. The aftermaths of the green revolution left the soils in most of the well-cultivable locations across the globe overloaded with residual pesticide and chemical effects. Conventional methods of agricultural improvement still rely much on the increased use of fertilizers and pesticides, leaving the soil exposed to the chemical vulnerability which drastically affects its organic content. This undesired chemical loading of soil not only affects the existing crop quality but also leads to augmented risks in aquatic environments, via eutrophication (Kalwasińska et al. 2011; Lew et al. 2013). Several studies discuss the potential risks of different metal- and metal oxide-based NPs, amongst which Ag, CuO and CeO_2 do pose a significant concern with regard to their polluting tendencies. The higher toxicity of Ag than Au seems to be due to its higher reactivity, which also imparts its substantially stronger antifungal attributes. Interestingly, CuO NPs have been recurrently proposed as toxic, affecting crop germination and growth from as low as 0.1 to 600 mg/L concentrations (Atha et al. 2012; Nair et al. 2014; Moon et al. 2014; Corral-Diaz et al. 2014; Saha and Dutta 2017). Such indications do pose a concern for NP usage but exact generalization about all NP kinds is relatively impractical. This is so as several other factors, like soil composition, geography, microbial content, organic content, water retention ability, pH and aggregation-promoting/aggregation-inhibiting response towards NPs, remain critical for inducing the toxic response of NPs. Thereby, it is impulsively desired to regulate the requirement driven fertilizer and pesticide delivery so that the concurrent damages could be arrested before acquiring irreversible extent.

3.1 Nanotechnology-Enabled Pesticide and Fertilizer Delivery

The emergence of nanoscale formulations having pesticides and fertilizers in dissolved form has emerged as a reliable solution to this problem. The nanoemulsions enable uniform distribution of pesticide and fertilizer droplets, owing to which much lower concentration of chemicals goes to the soil being treated. Nanodispersions carrying nano-encapsulated pesticides enable their controlled release at the desired sites, alongside preventing the premature degradation and reactivity of carrier molecules. This would enable a much lesser amount of pesticides being used (which eases the economic pressure) and also ensure its effective usage at the desired rate, thereby causing little damage to the soil texture (Chen et al. 2011). A systematic understanding of nanofertilizers is provided by Kah et al., categorized into three broad categories, namely, (a) nanomaterials comprising of macronutrients, (b) nanomaterials comprising of micronutrients and (c) nanomaterials acting as carriers of macronutrients (Kah 2015). Unlike the first two categories, the third category does not use nanomaterials as nutrients, but as additives. The added nanomaterials could either be NPs or any other nanostructured material, where popular examples of three categories are hydroxyapatite, layered double hydroxides intercalated with phosphate ions and ZnO NPs (Koilraj and Kannan 2010, Novillo et al. 2014, Iftekhar et al. 2018). The products in the third category generally comprise a wide variety of materials that are like nutrient-loaded zeolites or some materials that are principally not considered as nanoscale material (biochar) (Servin et al. 2017). Several carrier systems using nanomaterials have been developed that facilitate effective delivery of active ingredients having insecticidal, fungicidal or herbicidal properties. Materials as diverse as silica NPs, carbon nanotubes, graphene oxide, solid-lipid NPs and polymers are being increasingly applied for nanoscale control in the delivery of pesticides. Amongst the inorganic nanomaterials, Cu NPs are widely used for their antifungal applications (Pyrzynska 2011; Rastogi et al. 2019; Beltrán-Partida et al. 2019).

3.2 NPs for Faster and Robust Sensing

The second potential area having witnessed the distinction of using nanomaterials is the application of NPs and nanosystems for monitoring the seed quality (such as the preharvest measure) as well as monitoring the standards of subsequent agricultural practices. The use of ultrasensitive NPs, such as Au, Ag, silica, Fe_3O_4 and several others, has enhanced the accuracy of sensing significantly compared to the conventional enzyme-controlled measures. There are two potential advantages of using these NPs: first is that they can be made using a variety of methods and in different sizes and geometry and second is that the quantum confinement effect in these entities makes them capable of detecting even a little attenuation in their SPR frequencies, owing to which even the minute-level changes in the sensed environments could be detected. The different shapes and geometries of these NPs are extremely handy incentives in some practical scale-up operations. For example, nanorods have an elongated surface, so they have the ability to detect pathogens or harmful stimulus over a large volume. Similarly, NPs of Au can be conjugated with quantum dots that detect foreign substances (even at picometer levels) through variations in their fluorescence properties. Likewise, where there is a risk of magnetically responsive contaminations, the magnetic NPs could be used. The key advantages with respect to conventional sensing methods are the detection limit (which is usually highly sensitive) and the efficacy of detection since higher chemical reactivity and larger surface areas enhance the binding activities of detection agents.

The distinct performance of nanomaterial conferred sensing could be viewed in a 2006 study, proposing the utility of acidic polystyrene microparticle-based fluorescent sensor for detection of *Staphylococcus aureus* enterotoxin B (SEB), a highly thermoresistant toxin, contaminating drinking water and milk samples. The sensing system comprised of polystyrene microparticles labelled with fluorescein isothiocyanate (FITC) and anti-SEB. Following SEB binding, the variations in fluorescence pattern of FITC were noted as estimators of SEB concentration, which was noted as low as 0.125 ng/mL in drinking water and 0.5 ng/mL in milk. So if microparticles can detect such limits of pathogens, extending the probe with NPs would replicate the detection limit to still lower limits (Medina 2006). Some other breakthrough sensing systems developed using Au, Ag NPs, CNTs, and quantum dots, operational either alone or in combination mode, are listed in Table 26.2 (Schofield et al. 2007; Chien et al. 2008; Radoi et al. 2008; Pathak et al. 2001; Taton et al. 2000; Jean et al. 2010; Liu et al. 2014; Han et al. 2015; Wang et al. 2008; Zhang et al. 2010; Li et al. 2015; Singh et al. 2012). These studies speak volumes about the extraordinary precision level of nanomaterials through their distinguished surface properties, thereby making the diagnosis not only faster but more accurate.

Table 26.2 Sensing distinctions attained by different nanomaterials, highlighting precision and detectable damage modes on reducing limits

NP type	Special attribute	Major application accomplished	Reference
Gold	Robust surface functionalization, detection of little quantities via spectrophotometric changes	Ten-minute detection of cholera toxin through GM1 ganglioside ECM terminal moiety recognition, Shiga-like toxin via globotriose conjugation and toxin B subunit interaction	Schofield et al. (2007) and Chien et al. (2008)
Iron oxide	Modulation of shape and magnetic response via controlling polymer addition time, variation of temperature and using specified capping agents	Used to detect and quantify aflatoxin from milk samples, following conjugation with membrane antibodies	Radoi et al. (2008)
QDs	Size-dependent optical excitation and relaxation, highly bright and extremely photostable	In vitro and in vivo detection of cancers, detection of Y-chromosome in fixed human sperm cells, detection of genetic diseases through low-target DNA concentrations	Pathak et al. (2001) and Taton et al. (2000)
Silica NPs	Core-shell structure enables higher stability, accuracy and sensitivity, ability of being used in combination with a range of other NPs	Detection of melamine when used in combination with Ag nanospheres, fluorescent detection of Cu NPs in tap water in combination with carbon dots	Jean et al. (2010) and Liu et al. (2014)
CNTs	Elongated sensing possibilities through a rod-shaped structure, tuneable geometry, extraordinary strength and electromechanical responses	Electrochemical detection of bisphenol A, organophosphorus pesticides, hydrazine and nitrides, calorimetric detection of melamine, ochratoxin A, mercury and silver	Han et al. (2015), Wang et al. (2008), Zhang et al. (2010), and Li et al. (2015)
ZnO NPs	Robust functionality, flexible design and surface modulation, range of synthesis options	Large-scale sensing of nitrogen dioxide, ability to sense free radicals through its native antioxidant traits	Singh et al. (2012)

3.3 Nanochips, Nanoarrays and Nano-Barcoding

The terminologies “chips, arrays and barcodes” are basically the molecular platforms for sensing a biomolecule, be it DNA, a live organism as a contaminant or any other. The prefix nano, with each methodology, infers the use of nanomaterials that range from a multitude of NPs to quantum dots and hybrid nanomaterials comprising of NPs immobilized on thin and flexible supports. The whole story revolves around the higher surface area of nanomaterials, which harbours the potential of storing greater information compared to conventional materials. The lower dimensions of nanomaterials with their faster electromechanical response (triggered by their constricted energy levels) not only enhance the detection level but also occupy much lesser space alongside enabling flexible handling and control. With nanoscale dimensions, multiple analysis could be done at the same time as compared to the conventional array and chip technology. Biochips are devices which have cross-linked networks on their surface that could be immobilized with sensing probes or curative elements for any internal injury. Though studies with nanochip development are presently restricted to animal models, they have established a reliable method of gene replacement using an electric field to deliver specific genes to the tissues underlying the skin layer (Kricka 2000). The replication of this technology to the seeds of crop plants could enable the seeds with desired gene expression thereby minimizing the productivity uncertainty and could even be used to test new and more efficient stress-tolerant species. Similarly, barcodes are the assembly of parallel devices containing information about any product (anything in the grocery shop or medical dispensary). The use of nanomaterials, having high aspect ratios, could revolutionize this technology by occupying less space and containing much higher information. Storing information on a nanomaterial will obviously provide the benefit of having greater information within a small space. The functioning of these materials is critically affected by the encoding stimulus, which varies according to the intended purpose. The stimulus used for coding varies from being fluorescently sensitive, optically active, magnetically active or even heat sensitive. Each code, therefore, could be tracked only in a specific manner, thereby providing exclusive information storage for systematic record maintenance. Tagging such specific labels to seeds having unique attributes in any of the growth features could facilitate a predictable study of combining differing features (Shikha et al. 2017; Valentini et al. 2017). For example, stress-tolerant species could be tagged using antibodies while species tolerant to salinity could be selected with a marker delivering more salt. In this way, the selection of seeds with desired features could be fastened and crop productivity could be improved, irrespective of the geographical conditions. Though such conceptualizations are in the research phase, they have proved effective on lab-scale samples. To replicate these performances to the agricultural fields, several factors need to be optimized, the foremost of which is an unpredictable climate. In this context, modelling techniques exercising controls on the varying parameters could be helpful. Trials for commercialization are in progress but limited to developed countries only.

3.4 Sustainable Use of Agrochemicals Using Nanoplatforms

Apart from pesticides and fertilizers, a number of other chemicals are also needed to regulate crop growth at different stages. These chemicals could be the growth factors, microbial proteins, materials enriching the organic content of a particular soil, detoxifying bacteria and other microbes. Although the impacts of adding such materials using nanocarriers have still not been commercialized, on the contrary the studies suggest that with nanoscale devices and control features, 20–30% gain in crop productivity could be attained. A substantial concern in this regard arises from the concern that whether this gain is considerable with respect to the expenditure incurred in implementing the nanocarrier-mediated delivery of these chemicals. Studies focused on this assessment reveal a gloomy picture, with multiple trials facing obstructions due to the scarcity of public funding (Mukhopadhyay 2014; Report of the National Nanotechnology Initiative Workshop; Arlington, VA, USA 2009). Furthermore, though results on a small scale have been promising, establishing a clear picture from the viewpoint of a large agricultural field has proved to be rather impractical. This is because the crops grown in a field are always a witness of so many uncontrolled and unpreventable stresses and the conditions in the laboratory are significantly different. So attaining the nanoscale benefits of nanocarrier-delivered agrochemicals involves the optimization of several factors owing to which results are not yet being promisingly replicated. Oftentimes, the modified protocols could not be tested due to the ethical concerns being imposed on the food crops, enlightening the societal concern.

4 Useful Nanomaterials with Distinguished Mechanisms

Although reports on any major improvement in crop yield and quality of harvest are barely minimal, the laboratory-scale or research-level efforts frequently demonstrate nearly similar nanomaterials for obtaining improved crop response. The nanomaterials finding favour for such applications include inert NPs (substantially, Au and Ag), carbon nanotubes, quantum dots, nanorods and nanosuspensions. All these nanosystems are characterized by unique structural and functional attributes, making them suitable for faster and robust sensing, ability to be diversely functionalized and their inherent flexible nature (soft boundaries of nanosuspensions). The text ahead describes the unique features of several NPs and their integrated systems, describing the differences and key benefits of their singular and integrated application (Fig. 26.2).

4.1 Au and Ag NPs

NPs are primarily entities having sizes less than 100 nm. This size limit is not clearly defined and standardized, and therefore till 500 nm, several nanoscale properties are exhibited in variable extents (Babick et al. 2016). The Au NPs are one of the most widely used nanomaterials for faster and more efficient sensing because of three major reasons. The first is the availability of a wide variety of synthesis methods, utilizing low energy requirements from the external end. Preparation of Au NPs using plants, microbes and sodium citrate (burst method) could be traced in several eminent publications (Menon et al. 2017; Kimling et al. 2006). Such robust synthesis methodologies make the preparation of Au NPs an eco-friendly and inexpensive

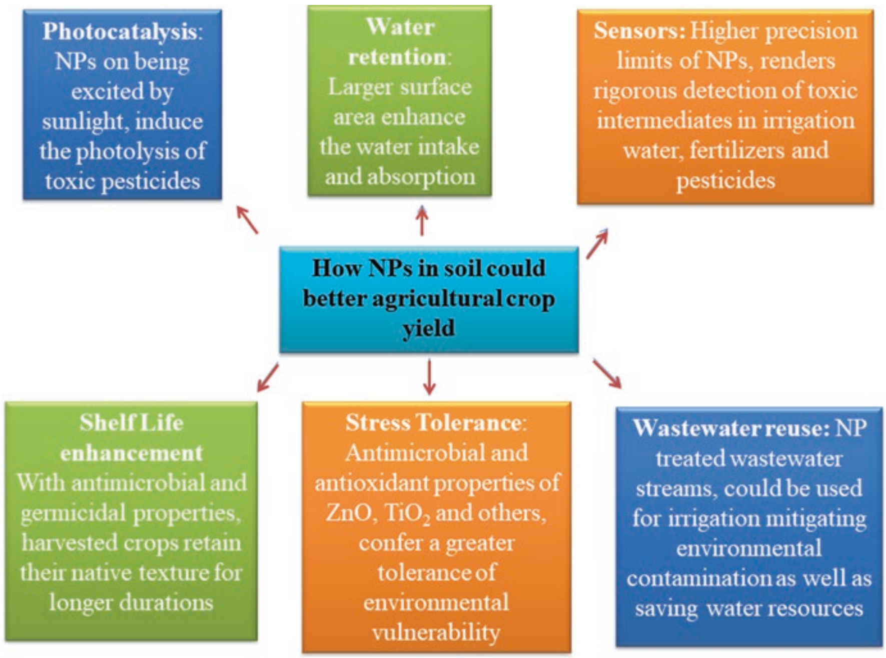

Fig. 26.2 The specific advantages of supplementing NPs to agriculturally lucid soils, projecting the usefulness of metal and metal oxide NP robust responses

process, which is the prime reason for their increasing multiple applications. The second reason for preferential Au NP usage is the availability of different shapes and geometries, which remains significantly important as properties at nanoscale remain implicit functions of their size and shape. At the same time, the elongated rod shape is capable of some exclusive functions which the spherical shape cannot perform. For sensing purposes, generally spherical or rod shapes are employed, which exhibit a characteristic plasmon resonance peak due to the coherent existence of free electrons in the conduction band. Interaction or binding with any stimulus at or adjacent to the surface results in changes in the SPR peak of the native nanomaterial and a proportionate change in any of the size-dependent characteristic properties. The third reason for increasing preference for Au NPs is the low reactivity of Au, making the development of conjugated assays easier, simpler and easily controllable (Zhao et al. 2008). Similar to Au, Ag NPs can also be prepared in various shapes and geometries; through changes in a precursor to reducing agent stoichiometry, the triangular, spherical and rod shapes are well known. The capability of being available in so many diverse shapes with easier and greener synthesis methods is the reason for their highly precise sensing applications in that a stimulus <1 nm could be easily detected. These particles are not only fitted to function as improved sensing agents but these can also be fed directly to the soil, where the nutrient replenishment via degradation of texturally and compositionally complex chemical substances can be fastened. Strategies with combined delivery of genetically modified microorganisms and these NPs are in active consideration, since many bacterial species can metabolize these NPs, and thereafter, the enzymatic controls in their body could be highly potent biocatalysts for enhancing soil fertility (Pallavi et al. 2016).

4.2 *Carbon Nanotubes (CNTs)*

One of the well-understood nanostructures, CNTs, prevails in cylindrical morphology, with two distinctly characterized forms, known as single-walled and multiwalled. Multiwalled nanotubes (MWNTs) are more common and readily prepared but single-walled nanotubes (SWNTs) are isolated from MWNTs following purification. The advantage with these nanostructures is that their cylindrical and elongated structure allows for multiple complementary binding sites, making the sensing quicker and more robust. Additionally, their compatibility with the carbon skeleton (an inherent constituent of these materials) makes them feasible for multiple functionalizations, so there is always an incentive of preparing need-based sensing probes. Recently, many studies have demonstrated a preferential uptake of these nanostructures at varying time intervals of the identification of damage or a troubled metabolic abnormality (Kobayashi et al. 2017; Liu et al. 2013). Since cylindrical nanostructures can stay longer within the physiological boundaries, so a number of modifications are being rapidly pursued to prolong their physiological existence. Such controls have facilitated the delivery of drugs in a time-phased manner, allowing for systemic regulation of disease cure analysis. Apart from their elongated structure, the arrangement of carbon atoms in these structures accomplishes them a conducting and semiconducting behaviour, allowing for simultaneous sensing possibility. The only concern behind using these nanomaterials is the restriction of their vulnerable toxic responses, whereby the risk of cross-reactivity could reach an uncontrollable extent. With recent advances and understanding of functionalization, better structural and morphological controls are being exercised to attune the biocompatibility of these materials. For multidisciplinary biological advances of CNTs, readers are suggested to have a look at numerous resourceful literature contributions (Kumar et al. 2017; Bekyarova et al. 2005; Schnorr and Swager 2011).

4.3 *Quantum Dots (QDs)*

After NPs and CNTs, QDs are the next nanomaterials which are theoretically well understood. These nanomaterials restrict their constituent free electrons and constituent atoms in all three dimensions, which makes it possible to perform multiple analyses at the same time, thereby saving overall resources of materials. A range of compositions is documented for the diversely studied QDs, each working on its own specific fluorescence sensitivity (Rosi and Mirkin 2005). For example, the

CdSe-based QDs are not preferred for delivering drugs due to Cd and Se toxicity, whereas QDs made up of only Si or P are more readily used for drug delivery. The three-dimensional quantum confinements (of charge carriers) in these nanomaterials allow a higher size control, paving the way for even slight changes in the fluorescence intensities. Once a specific toxin or harmful species binds to the QD-based sensing probe, its accurate estimation is facilitated through changes in the fluorescence intensity. Nowadays, faster diagnosis applications are being conceptualized via tagging fluorescent active biocompatible dyes with QDs and using the entire assembly as sensing probe. Higher photosensitivity of QDs along with the smaller dimensions enables their channelling into plant roots, where seed germination and nutrient absorption processes could be regulated via photocatalytic attributes (Bakalova et al. 2004; Das et al. 2015). The only concern regarding the QD use relates to their unpredictable metabolic responses, which could result in the enhancement of oxidative stress via generation of free radicals (Liu et al. 2011). Therefore, regulatory cautions evaluating proper monitoring of working efficacy external to the cellular environment should be practised to minimize unpredictable vulnerabilities.

4.4 Nanoemulsions and Nanosuspensions

As also detailed in the section of improved pesticide and fertilizer delivery, nanoemulsions are fluidic systems that allow controlled expression of a particular compound or species, through its sustained interactions. These systems are ideal carriers for a progressively controlled expression of organic compounds which are, otherwise, water-insoluble, remain poorly absorbed and could result in undesired chemical toxicities. With potential substitutes of surfactant-like molecules, the nanoemulsions prepared using non-ionic surfactants are highly suitable for drug and nutrient delivery to remote locations. The advantage of using non-ionic surfactants is that these systems do not require pH optimization before practical implementation and the toxicity of these systems is much lower, owing to the low chemical reactivity of non-ionic surfactants than their ionic counterparts. Nowadays, amino acids, protein-derived secondary biomolecules and plant metabolites have ably replaced the use of ionic surfactants (Mcclements et al. 2007; McClements 2004). The inclusion of such materials has not only reduced the toxicity associated with conventional surfactants but also reduced the energy required to make the nanoemulsions. Enhanced expression of pesticides, fungicides or any other complex fertilizer could be engineered through increased kinetic stability of nanoemulsions, allowing enhanced Brownian motions and interactions mediated through multiple binding sites. The implicit advantage of using such systems is the effective delivery of intended compounds at very low concentrations compared to conventional systems, which is highly instrumental to control the toxic responses. An alternative terminology of nanoemulsions is nanosuspension or microemulsion, differing on the basis of particle sizes and the use of external energy (for intended thermodynamic stability), with all other functional activities remaining the same. It is obvious that the smaller the particle size or the higher the distribution, the greater will be the nullification of gravitational effects or coalescence-related turbulence. So the smaller size of emulsions (in nanoemulsions) allows for greater enhancement in the dispersed phase chemical expression. Some nanoemulsion models optimized to deliver pesticides and nutrients in crop plants are listed in Table 26.3, where pH and stoichiometric composition of constituent phases play a critical role in attaining the homogeneous expression of the dispersed phase (Jiang et al. 2011; Kumar et al. 2004; Yang et al. 2009; Casanova et al. 2005; Wang et al. 2007; Wilson et al. US Patent Number 2011/0052654 A1; Latheef et al. 1993; Arthur 1999; Takei et al. 2008).

4.5 ZnO, Fe_3O_4 and TiO_2 NPs

Apart from the above-mentioned nanomaterials, ZnO, TiO_2 and Fe_3O_4 NPs have been well studied for their antioxidant and antimicrobial attributes, which jointly provide optimum growth conditions to various crop plants. For example, deficiency of Zn is the most common micronutrient adversity affecting the crop yield in alkaline soils. Soils that are too alkaline (due to aggravated $CaCO_3$ levels) often hinder the right Zn availability to crop plants due to the interference caused by high pH and $CaCO_3$-initiated Zn absorption and precipitation. In such circumstances, the use of ZnO NPs can help increase Zn bioavailability to crop plants, as compared to micron- or millimetre-sized Zn particles in conventional Zn fertilizers (ZnO and $ZnSO_4$). A number of leaf extracts have been used to synthesize ZnO NPs, providing remarkable control on size limits through adjusting the precursor-reducing agent stoichiometries. For example, *Moringa oleifera* leaf extract has been used to obtain 16–20-nm ZnO NPs that have further provided antibacterial and antifungal responses towards *Staphylococcus aureus*, *Bacillus subtilis*, *Pseudomonas aeruginosa*, *Proteus mirabilis*, *Escherichia coli* and *Candida albicans* and *Candida tropicalis* species. Maximum activity was noted against *Staphylococcus aureus* (Elumalai et al. 2015). Similarly, *Parthenium* leaf extracts have been used to prepare spherical and hexagonal ZnO NPs of up to 32- and 86-nm sizes, which subsequently showed varying antifungal responses towards *Aspergillus flavus* and *Aspergillus niger* (Rajiv et al. 2013). Spherical ZnO NPs, sized between 23 and 57 nm using zinc acetate and sodium hydroxide, have been evaluated against *Escherichia coli*, *Pseudomonas aeruginosa* (ATCC 15442), *Staphylococcus aureus* (ATCC 6538) and *Bacillus thuringiensis* (ATCC 10792), where all, except *Pseudomonas aeruginosa*, showed resistance to ZnO NPs.

Like ZnO, TiO_2 is a widely used photocatalyst, where Ti is known to catalyze the production of carbohydrates that increases the rate of photosynthesis and growth (Owolade et al. 2008; Khodakovskaya and Lahiani 2014; Chen et al. 2014). The photocatalytic attributes of TiO_2 have aided in its pesticide degradation and also towards plant protection as TiO_2 does not form any toxic and dangerous compounds

Table 26.3 Commercialized nanoemulsion- and nanoparticle-based pesticide/herbicide/insecticide delivery systems. The option of varying constitutional stoichiometries offers considerable advantages to control textural properties of encapsulated compounds, to minimize their adverse reactivity

Compound delivered	Key regulatory activity	Major advance notified	Reference
Nanoemulsions			
Glyphosate (herbicide)	Broad-spectrum systemic herbicide and crop desiccant	Reduced soil and water pollution risks, better control for specific crop type	Jiang et al. (2011)
Imidacloprid (insecticide)	Controls sucking insects, termites, selective soil insects and fleas on pets	Delivery through nanoemulsions has enhanced applicability range through reduced cytotoxicity	Kumar et al. (2004)
Polyethylene glycol (PEG) NPs loaded with garlic oil via melt dispersion method (insecticide)	Antibacterial and antibiotic characteristics	>80% encapsulation efficacy over a 5-month period, slow and controlled release of oil, effective for stored products	Yang et al. (2009)
Nicotine carboxylate (insecticide)	Modulation of oxidative balance	Monomodal size distribution, increased bioactivity with decrease in the fatty acid chain length	Casanova et al. (2005)
β-Cypermethrin (broad-spectrum insecticide)	Neurodegeneration, reproductive failure, dermal and ophthalmologic toxicity	30 nm droplets using poly(oxyethylene) lauryl ether and methyl decanoate, increased bioefficacy and dissolution	Wang et al. (2007)
Nanoparticles			
Diazinon (organophosphate insecticide)	Inhibition of neurotransmitter activity	Poly (n-alkyl acrylate)-stabilized temperature-sensitive microcapsules; encapsulated formulation exhibited nearly 90% insect mortality over 8 weeks	Wilson et al. US patent number 2011/0052654 A1
Sulprofos (insecticide)	Inhibition of neurotransmitter activity	Ethyl cellulose-stabilized formulations showing good results against eggs and larvae of the tobacco budworm *Heliothis virescens* in cotton plants	Latheef et al. (1993)
Cyfluthrin (insecticide and pesticide)	Induces muscle weakness, shortness of breath, headache, nausea and seizures	Controlled release and long-term action towards rice weevil *Sitophilus oryzae* over an 8-month period	Arthur (1999)
Acetamiprid (an alkaline and high-temperature-sensitive insecticide)	Nicotinic activity against acetylcholine receptors	Diffusion-controlled 2–20-μm-sized microcapsules with improved thermal degradation, controlled liberation for up to 10 weeks	Takei et al. (2008)

(Pelaez et al. 2012). TiO_2 NPs prepared using *Psidium guajava* leaf extract (32.58 nm in size) have been studied against *Aeromonas hydrophila* (MTCC-1739), *Proteus mirabilis* (MTCC-442), *Escherichia coli* (MTCC-1677), *Staphylococcus aureus* (MTCC-3160) and *Pseudomonas aeruginosa* (MTCC-4030), where highest activities were noted against *Staphylococcus aureus* and *Escherichia coli*, at 20 μg/mL. The synthesized NPs showed higher antioxidant activity than ascorbic acid and also superseded the antibacterial activity of tetracycline (Santhoshkumar et al. 2014). Besides ZnO and TiO_2, delivery of iron oxide NPs is also being investigated to tackle iron deficiency in high pH and calcareous soils. Several studies document the effect of spraying iron oxide NPs on wheat growth, yield and quality. Improvements in spike and grain weight and biological and grain yield alongside grain protein content were noted altogether (Bakhtiari et al. 2015). Enhanced chlorophyll contents were noted in the subapical soybean leaves under the greenhouse test and hydroponic conditions, upon being subjected to a low concentration of superparamagnetic iron oxide NPs, with Fe NPs compensating the Fe deficiency via reduction of chlorotic symptoms (Ghafariyan et al. 2013). Fe NPs (at 500 mg/L) affected 47% increase in the number of pods in black-eyed peas, 7% increase in the seed weight and 10% enhancement in the chlorophyll content of leaves, where iron salt application proved less effective as compared to the Fe NPs alone (Delfani et al. 2014). Fe NPs bettered the beneficial effect of Mg NPs (frequently used as nanofertilizer) on black-eyed peas (Hoagland and Arnon 1950).

Thus, the different kinds of NPs show variable efficacy in improving the crop yield through bettering the responses of various growth control features, such as stress tolerance, optimized use of fertilizers and pesticides, providing metals as essential macro- or micronutrients and minimizing the unpredictability as well as a financial burden on the farmers.

5 Effect of Soil Type on the NP-Regulated Nutrient Regulation

Having a sound knowledge of soil chemistry is the foremost knowledge base to assure rightful return from the crop harvest since all crops are obviously not likely to grow equally well on the same kind of soil. Furthermore, even all NPs do not have a similar kind of working actions in the same soil variety which makes it important to study which kind of NPs are suitable for which kind of soil. Furthermore, the heterogeneous composition of soil characterized by its varied physicochemical properties such as pH, texture, organic content, water retention and others can alter the NP interacting behaviour once they are within the soil. Altogether, there are three main kinds of soil well known with respect to their compositional diversity and texture, namely, sandy, clayey and loamy. The particles in sandy soil are larger in size and have considerable spaces in between so that there is proper air circulation but little water retention. As a result, sandy soil cannot retain much water and is fit for the growth of only those plants that can survive water scarcity. Contrary to this, clayey soil has comparatively smaller-sized particles which are closely placed with each other, thereby resulting in higher water retention but poor aeration. Loamy soil is an intermediate within these two categories and has the right kind of particle size and interparticle separation. Comparing the suitability of NP activity in different soil types, the above differences reveal a better NP working efficacy in sandy soil, substantially because of the proper particle space. The only factor which needs to be assured is that the chemical composition of NPs should aid in optimal water retention and absorption. Soil microflora also occupies a central role in optimum nutrient absorption and distribution, such as in the case of rhizobium species occupying the root nodules in leguminous crops. Unless and until the rhizobium population is not in desired proportions, the nitrogen fixation extent of the host soil is inadequate, affecting the total protein content of agricultural soil. So the chosen NP concentrations and fed dosages should not be detrimental to the soil microbial population; otherwise, many useful functions of the soil could be inadvertently lost. Table 26.4 summarizes the concentration-dependent potential threats of various metal and metal oxide NPs in different soil varieties (Colman et al. 2013; Asadishad et al. 2017; Shah et al. 2014; Ge et al. 2012; Kumar et al. 2012; McGee et al. 2017).

Critical roles are depicted in hampering enzymatic activities and microbial population that have driven responses for the proper growth of crop plants. Several studies suggest exposure to fullerenes does not alter the structure and function of soil microflora, while nanoscale ZnO and TiO_2 particles have growth-inhibiting effects on the bacteria living inside the soil (Tan et al. 2018; Ge et al. 2011). To assure no loss in water retention capabilities of the host soil, natural zeolites are rapidly being used as potential alternatives to improve soil quality alongside the impacts of chemical and organic fertilizers (Najafi-Ghiri 2014). Nanozeolites facilitate slow release

Table 26.4 Soil-type-dependent toxicity of popularly used NP expressions (neat as well as oxidized forms)

Type of NP	Peculiar growth-dampening effect	Type of soil	Reference
Ag (0.14 $mg\cdot kg^{-1}$)	Attenuated bacterial activity through suppressed enzymatic activities	Sandy and sandy loam	Colman et al. (2013)
Au (0.1–100 $mg\cdot kg^{-1}$)	Significant effect on soil microflora and nutrient cycling	Sandy	Asadishad et al. (2017)
Fe, Ag and Co (550 mg pot)	No significant effect on microbial population (in collective mode) but individual activity affects bacterial activities	Acidic topsoil	Shah et al. (2014)
TiO_2 (20 $g\cdot kg^{-1}$)	Decrement and modification of bacterial diversity	Sandy clay loam	Ge et al. (2012)
Mixture of Cu, Ag and Si	Reduced C and N biomass along with modification of microbial community structure	Sandy peat Arctic soil	Kumar et al. (2012)
Ag, SiO_2 and Al_2O_3	Reduced dehydrogenase and urease activity, bacterial and archaeal amoA gene abundance	Pastureland soil	McGee et al. (2017)

of water sources and therefore increase the water-holding capacity of a soil (Manikandan and Subramanian 2014). Zeolites and nanozeolites improve the soil physical characteristics, such as water conduction, infiltration and ventilation, made possible by their porous and capillary properties. It is due to this reason that zeolite action keeps a particular soil uniformly aerated and that leads to zeolites being frequently termed as natural wetting agents, regulating the water conduction in plants (Szerment et al. 2014; Ghazavi 2015). Similarly, Si NPs are being used as relievers of the heavy metal toxicity risk in different soils as well as salinity stress and dehydration (Abdel-Haliem et al. 2017; Jullok et al. 2016). Most of the studies focusing on the effect of NP activities in the soil voice about their toxicity concerns although the exact mechanisms of the long-term manifestations are yet to be understood. In this context, it is of paramount importance to know about the peculiar source of NP entry to the soil, as there are numerous kinds of NPs which naturally prevail in every soil due to persistent environmental activities. A second major consideration is whether the NPs existing in any soil type are biologically or physically or chemically prepared. Studies predict that biologically prepared NPs are more compatible to crop plants since surface coatings (for aggregation prevention) are biocompatible in nature and most of the used biological sources (primarily leaf extracts or microbial population in subcultured fractions) are water soluble. Contrary to this, the NPs prepared through physical or chemical methods and are being used in electronic semiconducting applications or rather faster mechanical purposes bear chemically complex coatings on their surface. These coatings are not easily degraded and often result in agglomeration owing to the exposure towards host soil carrying several different kinds of materials with different reactivities. Increasing percentages of such nanomaterials often cause undesirable interference in seed germination, root and shoot growth and photosynthesis rate through diminishing chlorophyll concentrations. The risks present a gloomy picture beyond doubt because the effect at hand is practical of many significant proportions. Crops as common as onion, spinach, coriander, wheat, rice, soybean, mung bean, radish, lettuce, barley and cucumber have been affected in multifold undesirable extents (Shaw and Hossain 2013; Frazier et al. 2014; Hong et al. 2015; Yang et al. 2015; Rajput et al. 2018; Priester et al. 2017). In this reference, Josko et al. have reported the negative effect of high NP concentrations on dehydrogenase activity, while Janvier et al. and Suresh et al. reported their detrimental effect on the self-cleaning facilitated nutrient balancing, which considerably affects the plant nutrition and soil fertility (Josko et al. 2014; Janvier et al. 2007).

Typical factors ascertaining the harmful influences of NPs disposed to soil include their concentration, soil type and enzymatic activity. Soil properties, such as pH, chemical texture, structure and relative organic content, affect the microbial content of the soil as well as the ability of pollutant species to express toxic effects on the microorganisms (Fierer and Jackson 2006; Simonin and Richaume 2015). Not all soils are similarly affected by the NP exposure since there are some intentional preparations, such as supplementing the soil with digested and fly ash, which would reduce the pollutant bioavailability. Similarly, Calvario et al. in 2014 showed the role of particle size distribution and organic matter content (in the soil) as the critical factors affecting the microbial populations of host soil (Calvarro et al. 2014). Exposure to NPs is not always detrimental to the microbial and biological efficacy of the soil as revealed by the results of the studies on some intentionally prepared soils. Biochar, utilizing charcoal as a nutrient supplement to the soil, as soil amendment expresses minimal toxic effects of CeO_2 NPs on the plants grown, although NP- and biochar-amended soil interactions are not entirely studied (Servin et al. 2017).

6 Future Insights with Respect to Sustainable Progress Monitoring

Sustainable development is aimed at the optimum extraction of all potential benefits so that the advantage of one positive is not compromised or compensated by the negative of another aspect. Rather, the positive aspects of different contributing factors are expressed with reasonable control avoiding even a meagre negative expression of any of the variables. For instance, activities of NPs other than in the soil are finely regulated since a robust knowledge and database of potential alternatives is available for the NPs suitable in pesticide and fertilizer delivery or in the quantification of seed quality inspection, pathogen detection and related activities. Contrary to all such requirements (where the usage of NPs and nanomaterials is in our own hands and offers optional implementation, in sync with the intended purpose), the scenario where NP exposure to agricultural crops is accidental presents a differentiating aspect of NP activities. A careful look at the literature suggests repeated referrals to modelling several features of NP parameters so that the optimum combination of more than one attribute is attained (Raies and Bajic 2016; Valerio 2009; Deeb and Goodarzi 2012). For example, using an NP or nanocomposite system to deliver pesticides will ultimately deliver the nanomaterials to the soil after which it is well known that exposure of such nanomaterials to the soil could affect the soil texture and fertility through more than one way. In such circumstances, the choice needs to be rationally made so that the chosen nanosystem is moderately interactive which also aids in the controlled extent of pesticide delivery at the targeted site.

Making such a choice would simultaneously reassure or reduce any untoward chemical risk to the host soil so that the microbes existing in the soil are not hampered or affected wrongly. As studies till date mostly refer to critical detrimental effects on crop plant, there is a need to uptake scale-up models for studying the long-term NP effects (in terms of exposure dosages and duration). The risks with irregular NP toxic menaces are substantially due to their unceremoniously higher reactivity which could be a source of formation of heterogeneous and chemically more complex forms. Thus, modelling the nature of surface passivation materials with respect to the composition of a particular soil type in such cases could be the remedial measure. The next level of control could be exercised via collection of databases listing the harmful effects of NPs on different growth-regulating properties of crop plants. These insights could be useful to select the rightful NP concentrations and choose only those NPs which cause a lower negative influence on one factor and comparatively better effect on another. In vitro modelling of such permutations using computational techniques or docking could be a crucial link to choose optimal combinations. Physically and chemically prepared NPs generally possess chemically constituted aggregation-preventing coatings on their surfaces, which are hydrophobic in nature. Such artefacts are likely to complicate the degradation of NPs and ultimately increase their toxicity via an enhancement in oxidative stress (Manke et al. 2013; Saddick et al. 2017; Brown et al. 2004). The occurrence of such threats in several animals in the course of their drug delivery trials is proof of such vulnerable metabolic fates. The enzyme diversity of microbes is already a familiar part of several symbiotic associations between microbes and plants. Owing to a differential enzyme expression in microbial species alongwith the higher chemical reactivity of NPs and the dependence of enzyme activity on the working temperature, NPs having significantly distinct specificity (such as magnetic sensitivity, fluorescence sensitivity, antibiotic sensitivity, stress sensitivity or any other) could be utilized as need-based sensing agents. These entities have been used to monitor the stress levels of desalinated soils in terms of heavy metal pollution and another toxic constituent. NPs along with microbes serve as dual stress mitigating agents since microbes metabolize these harmful materials due to their greater stress tolerance levels and NPs do so by virtue of their higher surface areas. Furthermore, there could be a possibility that microbes metabolize these toxic species and synthesize them as NPs through enzymes of their metabolic machinery. In such interactions, it could be possible that modification in microbial genes could provide us with enhanced fluorescence or chemical responses towards any sensing material. This dual strategy could be a vital breakthrough as having more than one kind of NPs in the soil base could aid not only in detoxification but also in better nutrient and water absorption. The repercussions of such potential remedies are expressed via reduced water and more nutrient supply. Microbes with abilities to survive in < 0 and > 100 °C temperatures are enormous powerhouses to enhance the nanoscale specialities of NPs and other nanomaterials.

7 Conclusions

The application of nanoscale miniaturization tools has minimized agricultural uncertainties along with improvement in the qualitative and quantitative features of crop plants. The advantage of nanodevices towards exceptionally low-valued detection levels has monitored the seed quality and growth potential with more reliability. Faster and accurate sensing using NPs and integrated nanoprobes has improved disease detection and gene administration in obtaining wholesomely new and more stress-tolerant varieties. Though studies involving NP administration to crop plants project some serious inconclusive flaws, a proper selection of NP with reference to the soil concerned could minimize toxicity and crop quality deterioration issues.

The availability of nanocarriers with tuneable design features has already simplified the need-based targeted delivery of pesticides and fertilizers, thereby reducing the chemical hazards to soil and aquatic habitats. The optimization of NP usage is swiftly on the way of being better controlled, to detect the pathogen level, to enhance the photosynthesis rate through photocatalytic attributes and to detoxify the toxic soil ingredients via judicious utilization of solar energy. With a rapid interest in interdisciplinary studies, expectations to achieve better control on agricultural crop yields and their quality standards are significantly on a high.

References

Abdel-Haliem MEF, Hegazy HS, Hassan NS et al (2017) Effect of silica ions and nano silica on rice plants under salinity stress. Ecol Eng 99:282–289

Arthur FH (1999) Evaluation of an encapsulated formulation of cyfluthrin to control Sitophilus oryzae (L.) on stored wheat. J Stored Prod Res 35(2):159–166

Asadishad B, Chahal S, Cianciarelli V et al (2017) Effect of gold nanoparticles on extracellular nutrient-cycling enzyme activity and bacterial community in soil slurries: role of nanoparticle size and surface coating. Environ Sci Nano 4:907–918

Atha DH, Wang H, Petersen EJ et al (2012) Copper oxide nanoparticle mediated DNA damage in terrestrial plant models. Environ Sci Technol 46(3):1819–1827

Babick F, Mielke J, Wohlleben W et al (2016) How reliably can a material be classified as a nanomaterial? Available particle-sizing techniques at work. J Nanopart Res 18:158

Bakalova R, Ohba H, Zhelev Z et al (2004) Quantum dots as photosensitizers? Nat Biotechnol 22(11):1360–1361

Bakhtiari M, Moaveni P, Sani B (2015) The effect of iron nanoparticles spraying time and concentration on wheat. Biol Forum Int J 7(1):679–683

Bekyarova E, Ni Y, Malarkey EB et al (2005) Applications of carbon nanotubes in biotechnology and biomedicine. J Biomed Nanotechnol 1(1):3–17

Beltrán-Partida E, Valdez-Salas B, Valdez-Salas E et al (2019) Synthesis, characterization, and in situ antifungal and cytotoxicity evaluation of ascorbic acid-capped copper nanoparticles. J Nanomater Article ID 5287632

Brown DM, Donaldson K, Borm PJ et al (2004) Calcium and ROS-mediated activation of transcription factors and TNF-alpha cytokine gene expression in macrophages exposed to ultrafine particles. Am J Physiol Lung Cell Mol Physiol 286(2):344–353

Calvarro LM, de Santiago-Martín A, Gomez JQ et al (2014) Biological activity in metal contaminated calcareous agricultural soils: the role of the organic matter composition and the particle size distribution. Environ Sci Pollut Res 21(9):6176–6187

Casanova H, Araque P, Ortiz C (2005) Nicotine carboxylate insecticide emulsions: effect of the fatty acid chain length. J Agric Food Chem 53:9949–9953

Chen J, Wang W, Xu Y, Zhang X (2011) Slow-release formulation of a new biological pesticide, pyoluteorin, with mesoporous silica. J Agric Food Chem 59(1):307–311

Chen H, Seiber JN, Hotze M (2014) ACS select on nanotechnology in food and agriculture: a perspective on implications and applications. J Agric Food Chem 62(6):1209–1212

Chien YY, Jan MD, Adak AK et al (2008) Globotriose-functionalized gold nanoparticles as multivalent probes for Shiga-like toxin. Chembiochem 9:1100–1109

Collins RL, Doglia S, Mazak RA et al (1973) Controlled release of herbicides theory. Weed Sci 21:1–5

Colman BP, Arnaout CL, Anciaux S et al (2013) Low concentrations of silver nanoparticles in biosolids cause adverse ecosystem responses under realistic field scenario. PLoS One 8:57189

Corral-Diaz B, Peralta-Videa JR, Alvarez-Parrilla E et al (2014) Cerium oxide nanoparticles alter the antioxidant capacity but do not impact tuber ionome in *Raphanus sativus* (L). Plant Physiol Biochem 84:277–285

Das S, Wolfson BP, Tetard L et al (2015) Effect of N-acetyl cysteine coated CdS:Mn/ZnS quantum dots on seed germination and seedling growth of snow pea (*Pisum sativum* L.): imaging and spectroscopic studies. Environ Sci Nano 2(2):203–212

Deeb O, Goodarzi M (2012) In silico quantitative structure toxicity relationship of chemical compounds: some case studies. Curr Drug Saf 7(4):289–297

Delfani M, Firouzabadi MB, Farrokhi N et al (2014) Some physiological responses of black-eyed pea to iron and magnesium nanofertilizers. Commun Soil Sci Plant Anal 45(4):530–540

Devreese JT (2007) Importance of nanosensors: Feynman's vision and the birth of nanotechnology. Mater Res Soc Symp Proc. Materials Research Society 0952-F01-01

Elumalai K, Velmurugan S, Ravi S et al (2015) Green synthesis of zinc oxide nanoparticles using *Moringa oleifera* leaf extract and evaluation of its antimicrobial activity. Spectrochim Acta Mol Biomol Spectrosc 143:158–164

Fierer N, Jackson RB (2006) The diversity and biogeography of soil bacterial communities. PNAS 103(3):626–631

Forget G (1993) Balancing the need for pesticides with the risk to human health. In: Forget G, Goodman T, de Villiers A (eds) Impact of pesticide use on health in developing countries. IDRC, Ottawa, p 2

Frazier TP, Burklew CE, Zhang B (2014) Titanium dioxide nanoparticles affect the growth and microRNA expression of tobacco (*Nicotiana tabacum*). Funct Integr Genomics 14(1):75–83

Garrido-Herrera FJ, Daza-Fernandez I, Gonzalez-Pradas E et al (2009) Lignin-based formulations to prevent pesticides pollution. J Hazard Mater 168(1):220–225

Ge YG, Schimel JP, Holden PA (2011) Evidence for negative effects of TiO_2 and ZnO nanoparticles on soil bacterial communities. Environ Sci Technol 45(4):1659–1664

Ge YG, Schimel JP, Holden PA (2012) Identification of soil bacteria susceptible to TiO_2 and ZnO nanoparticles. Appl Environ Microbiol 78:6749–6758

Ghafariyan MH, Malakouti MJ, Dadpour MR et al (2013) Effects of magnetite nanoparticles on soybean chlorophyll. Environ Sci Technol 47(18):10645–10652

Ghazavi R (2015) The application effects of natural zeolite on soil runoff, soil drainage and some chemical soil properties in arid land área. Int J Innov Appl Stud 13(1):172–177

Gupta SK, Jani JP, Saiyed HN et al (1984) Health hazards in pesticide formulators exposed to a combination of pesticides. Indian J Med Res 79:666–672

Gupta R, Malik P, Das N, Singh M (2019) Antioxidant and physicochemical study of *Psidium guajava* prepared zinc oxide nanoparticles. J Mol Liq 275:749–767

Hamad AF, Han JH, Kim BC et al (2018) The intertwine of nanotechnology with the food industry. Saudi J Biol Sci 25(1):27–30

Han J, Li F, Jiang L et al (2015) Electrochemical determination of bisphenol a using a polyacrylamide-multiwalled carbon nanotube-modified glassy carbon electrode. Anal Methods 7(19):8220–8226

Hoagland DR, Arnon DI (1950) The water-culture method for growing plants without soil. Calif Agric Exp Station Circ 347:1–32

Hong J, Rico CM, Zhao L et al (2015) Toxic effects of copper-based nanoparticles or compounds to lettuce (*Lactuca sativa*) and alfalfa (*Medicago sativa*). Environ Sci Process Impact 17(1):177–185

Huang Q (2012) Nanotechnology in the food, beverage and nutraceutical industries. Woodhead Publishing Limited, Cambridge

Iftekhar S, Küçük ME, Srivastava V et al (2018) Application of zinc-aluminium layered double hydroxides for adsorptive removal of phosphate and sulfate: equilibrium, kinetic and thermodynamic. Chemosphere 209:470–479

Janvier C, Villeneuve F, Alabouvette C et al (2007) Soil health through soil disease suppression: which strategy from descriptors to indicators? Soil Biol Biochem 39:1–23

Jean RD, Chiu KC, Chen TH et al (2010) Functionalized silica nanoparticles by nanometallic ag decoration for optical sensing of organic molecule. J Phys Chem C 114(37):15633–15639

Jiang LC, Basri M, Omar D et al (2011) Physicochemical characterization of non-ionic surfactants in oil-in-water (o/w) nanoemulsions for new pesticide formulations. Int J Appl Sci Technol 1:131–142

Josko I, Oleszczuk P, Futa B (2014) The effect of inorganic nanoparticles (ZnO, Cr_2O_3, CuO and Ni) and their bulk counterparts on enzyme activities in different soils. Geoderma 232-234:528–537

Jullok N, Van Hooghten R, Luis P, Volodin A, Van Haesendonck C, Vermant J, Van der BB (2016) J Clean Prod 112:4879–4889

Kah M (2015) Nanopesticides and nanofertilizers: emerging contaminants or opportunities for risk mitigation? Front Chem 3:64

Kalia A, Parshad VR (2015) Novel trends to revolutionize preservation and packaging of fruits/fruit products: microbiological and nanotechnological perspectives. Crit Rev Food Sci Nutr 55(2):159–182

Kalwasińska A, Kęsy J, Wik I et al (2011) Neustonic versus epiphytic bacteria of eutrophic lake and their biodegradation ability on deltamethrin. Biodegradation 22:699–707

Keating BA, Carberry PS, Bindraban PS et al (2010) Eco-efficient agriculture: concepts, challenges and opportunities. Crop Sci 50:S109–S119 [Symposia]

Khodakovskaya MV, Lahiani MH (2014) Nanoparticles and plants: from toxicity to activation of growth. In: Sahu SC, Casciano DA (eds) Handbook of nanotoxicology, nanomedicine and stem cell use in toxicology. Wiley Sciences, pp 121–130

Kimling J, Maier M, Okenve B, Kotaidis V, Ballot H, Plech A (2006) Turkevich method for gold nanoparticle synthesis revisited. J Phys Chem B 110(32):15700–15707

Kobayashi N, Izumi H, Morimoto Y (2017) Review of toxicity studies of carbon nanotubes. J Occup Health 59(5):394–407

Koilraj P, Kannan S (2010) Phosphate uptake behaviour of ZnAlZr ternary layered hydroxides through surface precipitation. J Colloid Interface Sci 341:289–297

Kole RK, Banerjee H, Bhattacharyya A et al (1999) Phototransformation of some pesticides. J Indian Chem Soc 76(11–12):595–600

Kricka LJ (2000) Microchips, microarrays, biochips and nanochips – personal laboratories for the 21st century. EJIFCC 12(4):105–108

Kumar J, Singh G, Walia S et al (2004) Controlled release formulations of Imidacloprid: water and soil release kinetics. Pestic Res J 16:13–17

Kumar N, Shah V, Walker VK (2012) Influence of a nanoparticle mixture on an arctic soil community. Environ Toxicol Chem 31:131–135

Kumar S, Rani R, Dilbaghi N et al (2017) Carbon nanotubes: a novel material for multifaceted applications in human healthcare. Chem Soc Rev 46(1):158–196

Kydd J (2002) Agriculture and rural livelihoods: is globalisation opening or blocking paths out of rural poverty? Agricultural research and extension network paper no.121, ISBN 085003 5856

Latheef MA, Dailey OD Jr, Franz E (1993) Efficacy of polymeric controlled release formulations of sulprofos against tobacco budworm, Heliothis virescens (Lepidopetea: Noctuidae) on cotton. In: Berger PD, Devisetty BN, Hall FR (eds) Pesticide formulations and applications systems: 13th volume, ASTM STP 1183. American Society for Testing and Materials, Philadelphia, pp 300–311

Lew S, Lew SM, Biedunkiewicz A, Szarek J (2013) Impact of pesticide contamination on aquatic microorganism populations in the littoral zone. Arch Environ Contam Toxicol 64:399–409

Li Y, Xu J, Sun C (2015) Chemical sensors and biosensors for the detection of melamine. RSC Adv 5:1125–1147

Liu W, Zhang S, Wang L et al (2011) CdSe quantum dot (QD)-induced morphological and functional impairments to liver in mice. PLoS One 6:24406

Liu Y, Zhao Y, Sun B, Chen C (2013) Understanding the toxicity of carbon nanotubes. Acc Chem Res 46(3):702–713

Liu X, Zhang N, Bing T et al (2014) Carbon dots based dual-emission silica nanoparticles as a ratiometric nanosensor for Cu^{2+}. Anal Chem 86(5):2289–2296

Mahadevan R (2003) Productivity growth in Indian agriculture: the role of globalization and economic reform. Asia-Pac Dev J 10(2):57–72

Malik P, Katyal V, Malik V et al (2013) Nanobiosensors: concepts and variations. ISRN Nanomater Article ID 327435

Malik P, Shankar R, Malik V et al (2014) Green chemistry based benign routes for nanoparticle synthesis. J Nanopart Article ID 302429

Manikandan A, Subramanian KS (2014) Fabrication and characterization of nanoporous zeolite based N fertilizer. Afr J Agric Res 9(2):276–284

Manke A, Wang L, Rojanasakul Y (2013) Mechanisms of nanoparticle-induced oxidative stress and toxicity. Biomed Res Int:942916

Maruyama CR, Guilger M, Pascoli M et al (2016) Nanoparticles based on chitosan as carriers for the combined herbicides Imazapic and Imazapyr. Sci Rep 6:19768

Mathur SC (1999) Future of Indian pesticides industry in next millennium. Pestic Inf 24:9–23

McClements DJ (2004) Protein-stabilized emulsions. Curr Opin Colloid Interface Sci 9(5):305–313

McClements DJ, Decker EA, Weiss J (2007) Emulsion-based delivery systems for lipophilic bioactive components. J Food Sci 72(8):R109–R124

McGee CF, Storey S, Clipson N et al (2017) Soil microbial community responses to contamination with silver, aluminium oxide and silicon dioxide nanoparticles. Ecotoxicology 26(3):449–458

Medina MB (2006) Development of a fluorescent latex microparticle immunoassay for the detection of *Staphylococcal Enterotoxin* B (SEB). J Agric Food Chem 54(14):4937–4942

Menon S, Rajeshkumar S, Kumar V (2017) A review on biogenic synthesis of gold nanoparticles, characterization, and its applications. Res Effic Technol 3(4):516–527

Miller G, Senjen R (2008) Out of the laboratory and on to our plates nanotechnology in food and agriculture. Friends of the Earth

Moon YS, Park ES, Kim TO, Lee HS, Lee SE (2014) SELDI-TOF MS-based discovery of a biomarker in *Cucumis sativus* seeds exposed to CuO nanoparticles. Environ Toxicol Phar 38:922–931

Mukhopadhyay SS (2014) Nanotechnology in agriculture: prospects and constraints. Nanotechnol Sci Appl 7:63–71

Nair PMG, Kim SH, Chung IM (2014) Copper oxide nanoparticle toxicity in mung bean (*Vigna radiata* L.) seedlings: physiological and molecular level responses of in vitro grown plants. Acta Physiol Plant 36:2947–2958

Najafi-Ghiri M (2014) Effects of zeolite and vermicompost applications on potassium release from calcareous soils. Soil Water Res 9(1):31–37

Nanowerk (Webpage). Nanotechnology products and applications. Product: Guard IN Fresh. Honolulu, HI; Nanowerk; 2014. Available from: http://www.nanowerk.com/products/product. Accessed 19 Apr 2014

Nanowerk (Webpage). Nanotechnology products and applications. Product: NanoCeram-PAC. Honolulu, HI: Nanowerk; 2014. Available from: http://www.nanowerk.com/products/product. Accessed 19 Apr 2014

Novillo C, Guaya D, Avendano AAP et al (2014) Evaluation of phosphate removal capacity of Mg/Al layered double hydroxides from aqueous solutions. Fuel 138:72–79

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

Owolade O, Ogunleti D, Adenekan M (2008) Titanium dioxide effects disease development and yield of edible cowpea. Electron J Environ Agric Food Chem 7:2942–2947

Pallavi MCM, Srivastava R et al (2016) Impact assessment of silver nanoparticles on plant growth and soil bacterial diversity. 3 Biotech 6:254

Pathak S, Choi SK, Arnheim N et al (2001) Hydroxylated quantum dots as luminescent probes for in situ hybridization. J Am Chem Soc 123(17):4103–4104

Patolsky F, Lieber CM (2005) Nanowire nanosensors. Mater Today 8(4):20–28

Pelaez M, Nolan NT, Pillai SC et al (2012) A review on the visible light active titanium dioxide photocatalysts for environmental applications. Appl Catal B Environ 125(2012):331–349

Perlatti B, Bergo BPLS, da Silva MFGF, Fernandes JB, Forim MR (2013) (Chapter-20) Polymeric nanoparticle-based insecticides: a controlled release purpose for agrochemicals in insecticides – development of safer and more effective technologies, ed. Trdan S. INTECH Publishers

Priester JH, Moritz SC, Espinosa K et al (2017) Damage assessment for soybean cultivated in soil with either CeO_2 or ZnO manufactured nanomaterials. Sci Total Environ 579:1756–1768

Pyrzynska K (2011) Carbon nanotubes as sorbents in the analysis of pesticides. Chemosphere 83(11):1407–1413

Qureshi MA, Karthikeyan S, Punita K et al (2012) Application of nanotechnology in food and dairy processing: an overview. Pak J Food Sci 22(1):23–31

Radoi A, Targa M, Prieto-Simon B et al (2008) Enzyme-Linked Immunosorbent Assay (ELISA) based on superparamagnetic nanoparticles for aflatoxin M1 detection. Talanta 77(1):138–143

Raies AB, Bajic VB (2016) In silico toxicology: computational methods for the prediction of chemical toxicity. Wiley Interdiscip Rev Comput Mol Sci 6(2):147–172

Rajiv P, Rajeshwari S, Venckatesh R (2013) Bio-fabrication of zinc oxide nanoparticles using leaf extract of *Parthenium hysterophorus* L. and its size-dependent antifungal activity against plant fungal pathogens. Spectrochim Acta Mol Biomol Spectrosc 112:384–387

Rajput VD, Minkina T, Sushkova S et al (2018) Effect of nanoparticles on crops and soil microbial communities. J Soils Sediments 18(6):2179–2187

Rastogi A, Tripathi DK, Yadav S et al (2019) Application of silicon nanoparticles in agriculture. 3 Biotech 9(3):90

Rosi NL, Mirkin CA (2005) Nanostructures in biodiagnostics. Chem Rev 105(4):1547–1562

Roy A (2017) Synthesis of silver nanoparticles from medicinal plants and its biological applications: a review. Res Rev Biosci 12(4):138

Roychowdhury R, Abdel Gawwad MR, Banerjee U, Bishnu S, Tah J (2013a) Status, trends and prospects of organic farming in India: a review. J Plant Biol Res 2:38–48

Roychowdhury R, Banherjee U, Slofkova S, Tah J (2013b) Organic farming for crop improvement and sustainable agriculture in the era of climate change. OnLine J Biol Sci 13(2):50–65

Saddick S, Afifi M, Zinada OAA (2017) Effect of zinc nanoparticles on oxidative stress-related genes and antioxidant enzymes activity in the brain of *Oreochromis niloticus* and *Tilapia zillii*. Saudi J Biol Sci 24(7):1672–1678

Saha N, Dutta GS (2017) Low-dose toxicity of biogenic silver nanoparticles fabricated by *Swertia chirata* on root tips and flower buds of *Allium cepa*. J Hazard Mater 330:18–28

Santhoshkumar T, Rahuman AA, Jayaseelan C et al (2014) Green synthesis of titanium dioxide nanoparticles using *Psidium guajava* extract and its antibacterial and antioxidant properties. Asian Pac J Trop Med 7:968–976

Schnorr JM, Swager TM (2011) Emerging applications of carbon nanotubes. Chem Mater 23(3):646–657

Schofield CL, Field RA, Russell DA (2007) Glyconanoparticles for the colorimetric detection of cholera toxin. Anal Chem 79(4):1356–1361

Servin AD, De la Torre-Roche R, Castillo-Michel H et al (2017) Exposure of agricultural crops to nanoparticle CeO2 in biochar-amended soil. Plant Physiol Biochem 110:147–157

Shah V, Collins D, Walker VK et al (2014) The impact of engineered cobalt, iron, nickel and silver nanoparticles on soil bacterial diversity under field conditions. Environ Res Lett 9:024001

Sharma AK (2015) National council of applied economic research, Annual Report 2015–16

Shaw AK, Hossain Z (2013) Impact of nano-CuO stress on rice (*Oryza sativa* L.) seedlings. Chemosphere 93(6):906–915

Shikha S, Salafi T, Cheng J et al (2017) Versatile design and synthesis of nano-barcodes. Chem Soc Rev 46(22):7054–7093

Simonin M, Richaume A (2015) Impact of engineered nanoparticles on the activity, abundance, and diversity of soil microbial communities: a review. Environ Sci Pollut Res 22(18):13710–13723

Singh O, Kohli N, Singh RC (2012) Effect of pH on the morphology and gas sensing properties of ZnO nanostructures. Sensors Actuators B Chem 166:438–443

Snodgrass MM, Wallace LT (1980) Agricultural economics and resource management. Prentice Hall, Inc, New Delhi, pp 79–80

Szerment J, Ambrozewich-Nita A, Kedziora K et al (2014) Use of zeolite in agriculture and environmental protection. A short review. UDC 666(96):691.5

Takei T, Yoshida M, Hatate Y et al (2008) Preparation of polylactide/poly(ε-caprolactone) microspheres enclosing acetamiprid and evaluation of release behaviour. Polym Bull 61:391–397

Tan W, Peralta-Videa JR, Gardea-Torresdey JL (2018) Interaction of titanium dioxide nanoparticles with soil components and plants: current knowledge and future research needs-a critical review. Environ Sci Nano 5(2):257–278

Taton TA, Mirkin CA, Letsinger RL (2000) Scanometric DNA array detection with nanoparticle probes. Science 289(5485):1757–1760

The Nanoscale Science, Engineering, and Technology Subcommittee of the Committee on Technology of the National Science and Technology Council Nanotechnology-Enabled Sensing: Report of the National Nanotechnology Initiative Workshop; Arlington, VA, USA (2009)

The Project on Emerging Nanotechnologies (Webpage). Consumer products inventory. Washington, DC; 2013. Available from: http://www.nanotechproject.org/cpi. Accessed 19 Apr 2014

Valentini P, Galimberti A, Mezzasalma V et al (2017) DNA barcoding meets nanotechnology: development of a universal colorimetric test for food authentication. Angew Chem Int Ed 56:8094–8098

Valerio LG Jr (2009) In silico toxicology for the pharmaceutical sciences. Toxicol Appl Pharmacol 241(3):356–370

Wang L, Li X, Zhang G et al (2007) Oil-in-water nanoemulsions for pesticide formulations. J Colloid Interface Sci 314(1):230–235

Wang J, Timchalk C, Lin Y (2008) Carbon nanotube-based electrochemical sensor for assay of salivary cholinesterase enzyme activity: an exposure biomarker of organophosphate pesticides and nerve agents. Environ Sci Technol 42(7):2688–2693

Wilson SL, Boucher RE Jr, Inventors, Dow Agrosciences LLC., assignee. US Patent Number 2011/0052654 A1. 2010 Mar 1

Yang FL, Li XG, Zhu F et al (2009) Structural characterization of nanoparticles loaded with garlic essential oil and their insecticidal activity against *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae). J Agric and Food Chem 57(21):10156–10162

Yang Z, Chen J, Dou R et al (2015) Assessment of the phytotoxicity of metal oxide nanoparticles on two crop plants, maize (*Zea mays* L.) and rice (*Oryza sativa* L.). Int J Environ Res Public Health 12(12):15100–15109

Zhang L, Li T, Li B et al (2010) Carbon nanotube-DNA hybrid fluorescent sensor for sensitive and selective detection of mercury(ii) ion. Chem Commun 46(9):1476–1478

Zhao W, Ali MM, Aguirre SD et al (2008) Paper-based bioassays using gold nanoparticle colorimetric probes. Anal Chem 80(22):8431–8437