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REVIEW ARTICLE

Nanochemtechnology in Agriculture: An Environmental Sustainable Future

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ABSTRACT
Nanochemtechnology is progressively moved away from the experimental into the practical areas,like the development of slow/controlled release fertilizers, conditional release of pesticides and herbicides, on the basis of nanotechnology has become critically important for promoting the development of environment friendly and sustainable agriculture. The emerging new science and enabling technology, working with the smallest particle, the nanotechnology raises hope for new innovations in the field of chemistry, especially in agriculture. Nanochemtechnology applications in agriculture field include nonofertilizers, nonopesticides, nanoherbicides, etc.
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INTRODUCTION

Nanochemtechnology is a promising field of interdisciplinary research. The potential uses and benefits of nanochemtechnology are enormous. Agriculture provides food for humans, directly and indirectly. As world population is increasing, it is necessary to use the modern technologies such as chem and nanochemtechnologies in agricultural sciences. Nanotechnology has been defined as relating to materials, systems and processes which operate at a scale of 100 nm or less.A large proportion of those living in developing countries face daily food shortages as a result of environmental impacts. For developing countries, the drive is to develop drought and pest resistantcrops, which also maximize yield.The application of nanochemtechnology to agriculture and food industries is also getting attention now a days. Nanochemtechnology is a novel scientific approach that involves the use of materials and equipment capable of manipulating physical as well as chemical properties of a substance at molecular levels. According to Royal Society, "Nanotechnologies are the design, characterization, production and application of structures, devices and systems by controlling shape and size at nanometer scale".Nowadays, nanochemtechnology is progressively moved away from the experimental into the practical areas. Attempts to apply nanochemtechnology in agriculture began with the growing realization that conventional farming technologies would neither be able to increase productivity any further nor restore ecosystems damaged by existing technologies back to their pristine state; in particular because the long-term effects of farming with "miracle seeds", in conjunction with irrigation, fertilizers, and pesticides, have been questioned both at the scientific and policy levels, and must be gradually phased out.

Nanochemtechnology has many applications in all stages of production, processing, storing, packaging and transport of agricultural products. Nanochemtechnology will revolutionize agriculture and food industry by innovation new techniques such as: Precision farming techniques, enhancing the ability of plants to absorb nutrients, more efficient and targeted use of inputs, disease detection and control diseases, withstand environmental pressures and effective systems for processing, storage and packaging. Many unsolved and bottle necks in the field of life sciences and agriculture could be addressed through Nanochemtechnology. More focused research is required in the area of energy, environment, crop improvement, disease management and efficient resource utilization for increasing the productivity, profit, without hampering the natural ecosystem. Agriculture is the backbone of most of the developing countries in which a major part of their income comes from agriculture sector and more than half of the population depends on it for their livelihood. The current global population is nearly 6 billion with 50% living in Asia. A large proportion of those livings in developing countries face daily food shortages as a result of environmental impacts or political instability, while in the developed world there is a food surplus. For developing countries, the drive is to develop drought and pest resistant crops which also maximize yield. nanochemtechnologic intervention in farming has bright prospects for improving the efficiency of nutrient use through nanoformulations of fertilizers, breaking yield barriers through nanochemtechnology, surveillance and control of pests and diseases, understanding mechanisms of host-parasite interactions at the molecular level, development of new-generation pesticides and their carriers, preservation and packaging of food and food additives, strengthening of natural fibers, removal of contaminants from soil and water, improving the shelf-life of vegetables and flowers, clay-based nanoresources for precision water management, reclamation of salt-affected soils, and stabilization of erosion-prone surfaces, to name a few.

AREAS OF NANO CHEMICAL SCIENCE RESEARCH IN AGRICULTURE AND FOOD SCIENCE

Contribution of nanoscience research in agriculture will be in the following areas[3]:

1 Food safety and biosecurity
2. Agriculture input efficiency
3. Wastage of products
4. Sustainable farm management
5. Improvement of low shelf life
6. Post harvest management
7. Disease and pest control

Role of Nanochemtechnology in agriculture

Nature is a great teacher, and nanochemtechnology applications in agriculture can be successful if natural processes are simulated in greater scientific sophistication/articulation for successful implementation. It has great potential to make agriculture more efficient by using nanosensors and nono agricultural chemicals. For example, the goal might be to make soils more capable in order to improve efficient nutrient use for greater productivity and better environmental security. Nutrient management with nanotechnology must rely on two important parameters, ie, ions must be present in plant-available forms in the soil system, and since nutrient transport in soil-plant systems relies on ion exchange (eg, NH_4^+ $H_2PO_4^-$, HPO_4^{2-}, PO_4^{3-}, Zn^{2+}), adsorption-desorption (eg, phosphorus nutrients) and solubility-precipitation (eg, iron) reactions, nanomaterials must facilitate processes that would ensure availability of nutrients to plants in the rate and manner that plants demand. Since clay minerals control these reactions, they could be used as receptacles.. Further opportunities for applying nanotechnology in agriculture lie in the areas of genetic improvement of plants, 35, 46 delivery of genes and drug molecules to specific sites at the cellular level in plants and animals, 47 and nanoarray-based technologies for gene expression in plants to overcome stress and development of sensors 48, 49 and protocols for its application in precision farming, 50 management of natural resources, early detection of pathogens and contaminants in food products, smart delivery systems for agrochemicals like fertilizers and pesticides, and integration of smart systems for food processing, packaging, and monitoring of agricultural and food system security. 51,52 With nanofertilizers 53 emerging as alternatives to conventional fertilizers, buildup of nutrients in soils and thereby eutrophication and contamination of drinking water may be eliminated.54,55.

Nanochemtechnology came only in recent years but the seed of research in this field starts growing nearly half century ago.[1] The use of nanomaterials specifically for the agricultural purposes are required for improving the fertilization processes, increases in yields through nutrients optimization and minimized the requirement of plant protection products.Overdependence on supplementary irrigation, vulnerability to climate, and poor input and energy conversion are the three dominant issues in the current agricultural production system, and nanochemtechnology could possibly reduce their impact. Also, it has been observed that nanoremediation could be effective not only in reducing the overall costs of cleaning up large contaminated sites, but also in decreasing clean-up time by eliminating the need for treatment and disposal of contaminated soil and reducing some contaminant concentrations to near zero, all in situ, although caution is required, especially for full-scale ecosystem-wide studies, to prevent any potential adverse environmental impacts. Nanosized formulation of mineral micronutrients may improve solubility and dispersion of of insoluble nutrients in soil, reduce soil absorption and fixation and increase the bio availability. 34 Much existing knowledge could possibly be translated to other areas with the help of nanotechnology. For example, soil acidity could possibly be ameliorated by the use of nanozeolites. The phenomenon of zeolites supplying bases and retaining smectite-kaolinite in a stable phase since the early Tertiary (geologic) period in tropical humid climates with plenty of Al^{3+} ions in the system has been reported in some soils of the Western Ghat in India. 56 Nanochentechnology has been extensively used in plant protection, processing, packaging transportation of agricultural products and quality control and environment management.[2].

Table 1. Relevant applications in agricultural nanotechnology and examples of successful applications at small scale or R&D stage.

	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 in plants	Neem oil (Azadirachta indica) nanoemulsion as larvicidal agent (VIT University, IN)	[1-19]
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)	[34]
Soil improvement			
Water/liquid retention	Nanomaterials, e.g. zeolites and nano-clays, for water or liquid agrochemicals retention in the soil for their slow release to the plants	Soil-enhancer product, based on a nano-clay component, for water retention and release (Geohumus-Frankfurt, DE	[38]
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 TiO2 nanoparticles for the photocatalytic degradation of agrochemicals in contaminated waters (University of Ulster, UK)	[17]
Diagnostic			
Nanosensors and diagnostic devices	Nanomaterials and nanostructures (e.g. electrochemically active 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)	[20]
Plant breeding			
Plant genetic modification	Nanoparticles carrying DNA or RNA to be delivered to plant cells for their genetic transformation or to trigger defence responses, activated by pathogens.	Mesoporus silica nanoparticles transporting DNA to transform plant cells (Iowa State university, US)	[13, 14]
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)	[22]

Nanoparticles and Nanopesticides

Nanoparticles like nanoforms of carbon, silver, silica, and alumino- silicates are used for controlling plant diseases. Pesticides inside nanoparticles are being developed that can be timed release or have release linked to an environmental trigger which is in contrast to our present system where either pesticides are applied or sprayed previously for the prevention or after the onset of diseases and pests. One of such effort is use of alumino silicates nanotubes with active ingredient. Nano pesticide formulation of carbofuran, thiram, imidacloprid, azadirachitin-A, and beta cyfluthrin are available in the market. Phosphate , zinc, nitrogen, iron, aluminium, silver, copper, and titanium based nanoparticles are used as fertilizers.[21

Nanoparticles of defined concentrations could be successfully used for the control of various plant diseases caused by several phytopathogens.

Nano silver: Nano silver is the most studied and utilized nano particle for bio-system. It has long been known to have strong inhibitory and bactericidal effects as well as a broad spectrum of antimicrobial activities. According to a study nano silica silver was found to be effective on 100% growth inhibition of many fungi and bacteria at 10 nm and 100 nm concentration respectively. Silver nanoparticles, which have high surface area and high fraction of surface atoms, have high antimicrobial effect as compared to the bulk silver. Antifungal effectiveness of colloidal nano silver (1.5 nm average diameter) solution, against rose powdery mildew caused by *Sphaerotheca pannosa* Var *rosae*. It is a very wide spread and common disease of both green house and outdoor grown roses. It causes leaf distortion, leaf curling, early defoliation and reduced flowering. Double capsulized nano silver was prepared by chemical reaction of silver ion with aid of physical method, reducing agent and stabilizers. They were highly stable and very well dispersive in aqueous solution. It eliminates unwanted microorganisms in planter soils and hydroponics systems. It is being used as foliar spray to stop fungi, moulds, rot and several other plant diseases. Moreover, silver is an excellent plant-growth stimulator.[26,27,28]

Iron nanoparticles : Application of zerovalent iron nanoparticles and even nanoparticles from iron rust could be harnessed for remediation of soils contaminated with pesticides, heavy metals, and radionuclides, given the high adsorption affinity these nanomaterials have for organic compounds and heavy metals. Iron nanoparticles also have excellent soil binding properties, similar to those of calcium carbonate nanoparticles, which help in formation of soil microaggregates and macroaggregates.[22]

Nano alumino-silicate: Leading chemical companies are now formulating efficient pesticides at nano scale. One of such effort is use of alumino-silicate nano tubes with active ingredients. The advantage is that alumino-silicate nanotubes sprayed on plant surfaces are easily picked up in insect hairs. Insects actively groom and consume pesticide-filled nanotubes. They are biologically more active and relatively more environmentally-safe pesticides. Silica nanoparticles have shown that mesoporous silica nano particles can deliver DNA and chemicals into plants thus, creating a powerful new tool for targeted delivery into plant cells.[24,25]

Titanium dioxide (TiO_2) nanoparticles: Titanium dioxide (TiO_2) is a non-toxic white pigment widely used in the manufacture of paints, study, ink, cosmetics, ceramics, leather, etc. and is a very strong disinfectant as compared to chlorine and ozone. Since TiO_2 is harmless, it is approved for use in food products upto 1% of product final weight. TiO_2 photocatalyst technique has great potential in various agricultural applications, including plant protection since it does not form toxic and dangerous compounds and possesses great pathogen disinfection efficiency. Scientists have been trying to improve the phytopathogenic disinfection efficiency of TiO_2 thin films by dye doping and other suitable methods (Yao *et al*., 2009).

Carbon nano materials: Among the various engineered nanomaterials, carbon based nanomaterials (such as single walled carbon nanotubes (SWCNTs), multi walled carbon nanotubes (MWCNTs), buckyballs, graphene, etc.), occupy a prominent position in various nano-biotechnology applications. Increased use and exposure to carbon nanomaterials could cause environmental concerns. Hence, it is extremely important to systematically study the effects that carbon nanomaterials in plants occupy a major component of the food chain.[5,29,30]

Magnetic nanoparticles: The scope of magnetic nanoparticles for site-targeted delivery of drugs has been exploited widely in biomedicine for the treatment of various diseases. However, in plant biology, such an application is still in its budding stage. Magnetic-based nano materials could be utilized for site-targeted delivery of systemic plant protection chemicals for the treatment of diseases that affect only specific regions of plants. If the movement of internalized magnetic nano materials could be tracked externally using high power external magnets, then it would be possible to direct them to specific areas where the chemicals need to be released. The advantage of using carbon-based nano materials (such as SWCNTs and MWCNTs) functionalized with magnetic nano particles is that the internal space allows filling of suitable plant protecting chemicals and the functionalized magnetic nano particles allow external control of the movement of nano carriers inside the plant system.[21,29]

PLANT PATHOGENS IN BIOSYNTHESIS OF NANOPARTICLES

The research on nano science and nanotechnology essentially involves preparation and use of nanoparticles of various elements and compounds. Among various uses, nano particles are also being used as antimicrobial agents for plant disease management. Formation of nano particles can be achieved via several processes which may be either physical or chemical.

Fungi: Fungi are relatively recent in their use in synthesis of nano particles. There has been a shift from bacteria to fungi to be used as natural 'nanofactories' owing to easy downstream processing, easy handling and their ability to secrete a large amount of enzymes. However, fungi being eukaryotes are less amenable to genetic manipulation compared to prokaryotes. Therefore, any alteration of fungi at genetic level for synthesis of more nano particles would not be so easy. It is important to know the mechanism of synthesis of nano particles in microbial systems to get better control over shape, size and other desired properties of the synthesized nano materials.

Bacteria: Among microbes, prokaryotes have received the most attention for biosynthesis of nanoparticles. Bacteria have been used to biosynthesize mostly silver, gold, FeS and magnetite nanoparticles and quantum dots of cadmium sulphide (CdS), zinc sulphide (ZnS) and lead sulphide (PbS).

Plant virus: Plant virus especially spherical/icosahedra viruses represent the examples of naturally occurring nanomaterials or nanoparticles. The smallest plant viruses known till date is satellite tobacco necrosis virus measuring only 18 nm in diameter (Hoglund, 1986). Plant viruses are made up of single or double stranded RNA/DNA as genome which is encapsulated by a protein coat. The protein coat/shell structurally and functionally appears like a container carrying the nucleic acid molecule as cargo from one host to another. Their ability to infect, deliver nucleic acid genome to a specific site in host cell, replicate, package nucleic acid and come out of host cell precisely in an orderly manner have necessitated them to be used in nanotechnology.

Nanofertilizer

Fertilizers have an axial role in enhancing the food production. Nanotechnology has provided the feasibility of exploiting nano scale or nano structured materials as fertilizer carriers or controlled release vectors for building of so-called "smart fertilizer" as new facilities to enhance nutrient use efficiency and reduce costs of environmental protection. Nano fertilizer with quick absorption and optimized released of nutrients to the plants are likely to replace conventional fertilizer in future. Encapsulation or coating and binding of fertilizer (envelop, forms of semi permeable membrances coated by resin polymer, waxes, and sulphur) within nano particles are able to regulate the release of nutrients from the fertilizer capsule to match the uptake pattern of crop. Encapsulation of fertilizers within a nano particle is one of these new facilities which are done in three ways (1) the nutrient can be encapsulated inside nano porous materials, (2) coated with thin polymer film and (3) delivered as particle or emulsions of nano scales dimensions.

Using nano fertilizer to control delivery of nutrients can be a powerful tool towards attaining sustainable agriculture and environment. Excessive applications of nitrogen and phosphorus fertilizers affect the groundwater and also lead to eutrophication in aquatic ecosystem. the development of slow/controlled release fertilizers conditional release of pesticides and herbicides, on the basis of nanochemtechnology has become critically important for promoting the development of environment friendly and sustainable agriculture. Nano fertilizer could be used to reduce nitrogen loss due to leaching and emissions. They could allow foe selective release linked to time or environmental condition. Indeed, nanotechnology has provided the feasibility of exploiting nano scale or nano structured materials as fertilizer carriers or controlled-release vectors for building of so-called "smart fertilizer" as new facilities to enhance nutrient use efficiency and reduce costs of environmental protection. The formulation might increase fertilizer efficiency, save fertilizer resource, extend effective duration of nutrients supply of fertilizer into soil and can reduce leaching. In addition, nano fertilizers will combine nano devices in order to synchronize the release of fertilizer-N and -P with their uptake by crops, so preventing undesirable nutrient losses to soil, water and air via direct internalization by crops, and avoiding the interaction of nutrients with soil, microorganisms, water, and air.

Smart fertilizers might become reality through transformed formulation of conventional products
using nanotechnology. The nano structured formulation might permit fertilizer intelligently control the release speed of nutrients to match the uptake pattern of crop. Solubility and dispersion for mineral micronutrients cause Controlled release formulation [9]. Nano sized formulation of mineral micronutrients may improve solubility and dispersion of insoluble nutrients in soil, reduce soil absorption and fixation and increase the bioavailability leads to increased Nutrient uptake efficiency.

Nanostructured formulation might increase fertilizer efficiency and uptake ratio of the soil nutrients in crop production, and save fertilizer resource.[9] Controlled release modes have properties of both release rate and release pattern of nutrients for water-soluble fertilizers might be precisely controlled through encapsulation in envelope forms of semi-permeable membranes coated by resin-polymer, waxes and sulphur.[14] Effective duration of nutrient release has desirable property of Nano structured formulation, it can extend effective duration of nutrient supply of fertilizers into soil.[7,8] Nano structured formulation can reduce loss rate of fertilizer nutrients into soil by leaching and/or leaking.

Nanofabrication in Agriculture use

Nanofabrication could be defined as the design and manufacture of devices that measure dimensions in nanometers. It is a vibrant field, so many new classes of materials with innovative fabrication technology are expected to appear in the future. Current engineered nano materials are grouped into four classes, [19] ie, carbon-based materials, metal-based materials, dendrimers, and composites. It is difficult to generalize the processes of nanofabrication with accuracy, because they are fabricated by methods specific to the requirements of the materials themselves, and in many cases are protected by intellectual property rights. Nanofabricated materials containing plant nutrients can be used in aqueous suspension and hydrogel forms, so as to enable hazard-free application, easy storage, and a convenient delivery system.[11]

Conventionally, nanofabrication can proceed by scaling down integrated circuit fabrication involving removal of one atom at a time to obtain the desired structure (top-down approach) or by a more sophisticated hypothetical scheme involving assembly of a structure atom-by-atom (bottom-up approach). Industry has been applying a variety of techniques, including physical and chemical vapor deposition, laser ablation, arc discharge, lithography electron, laser, ultraviolet light, photons, X-ray, focused ion beams, scanning probes for nano deposition or nano machining of atoms, molecules, compounds or structures, nano imprinting (soft and hard), and self-assembly to generate nano materials/nano products or nano material-containing products.

Application of Nanochemtechnology

Application of nanochemtechnology is essential, given the millions of people worldwide who continue to lack access to safe water, reliable sources of energy, health care, education, and other basic human development needs.We can get accurate information through applications of nanochemtechnology for monitoring of soil conditions, environmental changes, plant diseases and plant health issues by targeted us of the inputs i.e fertilizers and pesticides. The opportunity for application of nanotechnology in agriculture is prodigious.[19] Nanochemtechnology application in agriculture can makes farming more targeted and scientific. Research on the applications of nanochemtechnology in agriculture is less than a decade old. Nevertheless, as conventional farming practices become increasingly inadequate, and needs have exceeded the carrying capacity of the terrestrial ecosystem, we have little option but to explore nanotechnology in all sectors of agriculture. Nanochemtechnology inventions including nanomembrances for irrigation, water purification, desalination and detoxification, nano-porous zeolite and attapulgite clays for water treatment and remediation and TiO_2 nanoparticles for catalytic degradation of water pollutants can improve the quality of water. Nanochemtechnology promises a breakthrough in improving our presently abysmal nutrient use efficiency through nano formulation of fertilizers, breaking yield and nutritional quality barriers through nanochemtechnology, surveillance and control of pests and diseases, understanding the mechanism of host-parasite interactions at the molecular scale, development of new-generation pesticides and safe carriers, preservation and packaging of food and food additives, strengthening of natural fiber, removal of contaminants from soil and water bodies, improving the shelf-life of vegetables and flowers, and use of clay minerals as receptacles for nano resources involving nutrient ion receptors, precision water management, regenerating soil fertility, reclamation of salt-affected soils, checking acidification of irrigated lands, and stabilization of erosion-prone surfaces, to name a few.[5,16,17] The nano scales carriers i.e nano tubes, for this purpose, can be used for delivering pesticides, fertilizers, plant growth regulators etc, efficiently to the target site. Revisiting our understanding of the theoretical foundations of the agricultural production system along the geosphere (pedosphere)-biosphere-atmosphere continuum coupled with application of advanced theories like the theory of chaos and string theory may open up new avenues. Improvement in the efficiency of herbicides through the use of nanochemtechnology could result greater production of crops.[13] The encapsulated nano herbicides are relevant which acts only when there is a spell of rainfall, which truly mimics the rainfed system. Nanochemtechnology requires a thorough understanding of science, as well as fabrication and material technology, in conjunction with knowledge of the agricultural production system.[18] The rigor of this challenge might attract brilliant minds to choose agriculture as a career. To achieve success in the field, human resources need sophisticated training, for which new instruction programs, especially at the graduate level, are urgently needed. Nanochemtechnology applications in agriculture value addition and preservation of crop can bring a positive change in agriculture scenario of India.[6]

CONCLUSION

Attempts to apply nanochemtechnology in agriculture began with the growing realization that conventional farming technologies would neither be able to increase productivity any further nor restore ecosystems damaged by existing technologies back to their pristine state; in particular because the long-term effects of farming with in conjunction with irrigation, fertilizers, and pesticides, have been questioned both at the scientific and policy levels, and must be gradually phased out. Nanochemtechnology offers a plethora of user friendly option in the agriculture. the effective and practical risk management strategies should be practiced during the technological developments .

REFERENCES

1. Nanoforum (2006). Nanotechnology in Agriculture and Food. A Nano forum report.
2. Kuzma J, VerHage P. (2006). Nanotechnology in Agriculture and Food Production: Anticipated Applications. Washington, DC, USA: Woodrow Wilson International.
3. Scott N, Chen H. (2013). Nanoscale science and engineering for agriculture and food systems. Industrial Biotechnology. 17–18.
4. Khot LR, Sankaran S, Maja JM, Ehsani R, Schuster EW. (2012). Applications of nano materials in agricultural production and crop protection: a review. Crop Prot. 35: 64–70.
5. Chen H, Yada R. (2011). Nanotechnologies in agriculture: new tools for sustainable development. Trends Food Sci Technol.22: 585–594.
6. Rai M, Ingle A. (2012). Role of nanotechnology in agriculture with special reference to management of insect pests. Appl Microbiol Biotechnol. 94:287–293.
7. Subramanian KS, Tarafdar JC. (2011). Prospects of nanotechnology in Indian farming. Indian J Agric Sci. 8: 887–893.
8. Sekhon BS. (2010). Food nanotechnology – an overview. Nanotechnol Sci Appl. 3: 1–15.
9. Mousavi SR, Rezaei M. (2011). Nanotechnology in agriculture and food production. J Appl Environ Biol Sci. 1: 414–419.
10. Sozer N, Kokini JL. (2009). Nanotechnology and its applications in the food sector. Trends Biotechnol. 27:82–89.
11. Shrivastava S, Dash D. (2009).Agrifood nanotechnology: a tiny revolution in food and agriculture. J Nanopart Res. 6: 1–14.
12. Nakache E, Poulain N, Candau F, Orecchioni AM, Irache JM. (1999).Biopolymer and polymer nanoparticles and their biomedical applications. In: Nalwa HS, editor. Handbook of Nanostructured Materials and Nanotechnology. New York, NY, USA: Academic Press;.
13. Drexler KE. (1986).Engines of creation: the coming era of nanotechnology. 1986. [Accessed June 9, 2014]. Available from: http://e-drexler.com/p/06/00/EOC Cover.html..
14. Tillman D, Cassman KG, Matson PA, Naylor R, Polasky S. (2002).Agricultural sustainability and intensive production practices. Nature. 418: 671–677.
15. Presley DR, Ransom MD, Kluitenberg GJ, Finnell PR. Effect of thirty years of irrigation on the genesis and morphology of two semi-arid soils in Kansas. Soil Sci Soc Am J. 2004; 68: 1916–1926.
16. Osterholm P, Astrom M. (2004).Quantification of current and future leaching of sulfur and metals from boreal acid sulfate soils, western Finland. Aust J Soil Res. 42: 547–551.
17. Mukhopadhyay SS. (2005).Weathering of soil minerals and distribution of elements: pedochemical aspects. Clay Res.;24:183–199.
18. Knorr W, Prentice IC, House JI, Holland EA.(2005). Long-term sensitivity of soil carbon turnover to warming. Nature. 433:298–302.
19. Hobbs PR, Sayre K, Gupta R. (2008).The role of conservation agriculture in sustainable agriculture. Philos Trans R Soc Lond B Biol Sci. 363: 543–555.
20. Karn B, Kuiken T, Otto M. (2009).Nanotechnology and in situ remediation: a review of the benefits and potential risks. Environ Health Perspect.;117: 1823–1831.
21. Maurice PA, Hochella MF. (2008).Nanoscale particles and processes: a new dimension in soil science. Adv Agron. 100:123–153.
22. Hochella MF, Jr, Lower SK, Maurice PA, et al. (2008).Nanominerals, mineral nanoparticles, and earth systems. Science. 319:1631–1635.
23. Waychunas GA, Kim CS, Banfield JA. (2005). Nanoparticulate iron oxide minerals in soils and sediments: unique properties and contaminant scavenging mechanisms. J Nanopart Res. 7: 409–433.
24. Biswas PP, Sharma PD. A new approach for estimating fertilizer response ratio – the Indian scenario. Indian Journal of Fertilizers. 2008;4: 59–62.
25. Li W, He Y, Wu J, Xu J. (2012).Extraction and characterization of natural soil nanoparticles from Chinese soils. Eur J Soil Sci. 63:754–761.
26. Wilson MA, Tran NH, Milev AS, Kannangara GSK, Volk H, Lu GQM. (2008).Nanomaterials in soils. Geoderma.; 146:291–302.

27. Theng BKG, Yuan G. Nanoparticles in the soil environment. Elements. 2008;4: 395–400.
28. Liu R, Lal R. (2012). Nanoenhanced materials for reclamation of mine lands and other degraded soils: a review. J Nanotechnol. ;2012: ID 461468.
29. Maysinger D. (2007). Nanoparticles and cells: good companions and doomed partnerships. Org Biomol Chem;5: 2335–2342.
30. Ahmed F, Arshi N, Kumar S, et al. (2013).Nanobiotechnology: scope and potential for crop improvement. In: Tuteja N, Gill SS, editors. Crop Improvement under Adverse Conditions. New York, NY, USA: Springer.
31. 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. May 5–7, (2009).
32. DeRosa MC, Monreal C, Schnitzer M, Walsh R, Sultan Y. Nanotechnology in fertilizers. Nat Nanotechnol. 2010;5: 91.
33. Mukhopadhyay SS, Sharma S. (2013).Nanoscience and nanotechnology: cracking prodigal farming. Journal of Bionanoscience.; 7:1–5.
34. Bhattacharya T, Pal DK, Srivastava P. (1999).Role of zeolites in persistence of high altitude ferruginous Alfisols of the humid tropical Western Ghats, India. Geoderma. 90:263–276.
35. Hillie T, Munasinghe M, Hlophe M, Deraniyagala Y. (2006). Nanotechnology, Water & Development Meridian Institute's Global Dialogue on Nanotechnology and the Poor: Opportunities and Risks (GNDP) Meridian Institute.
36. MacLurcan DC. (2014).Nanotechnology and developing countries. Part 1: What possibilities? 2005. [Accessed June 9, 2014].
37. ETC Group . (2004).Action Group on Erosion, Technology, and Conservation. Down on the farm: The impact of nano-scale technologies on food and agriculture. Ottawa, ON, Canada:. [Accessed June 9, 2014].
38. Singh M, Mukhopadhyay SS, Kiran-Jeet, Kalia A, Kaur R. (2013). Zinc in clay-mineral receptacles in nanoforms for their use as advance materials including novel fertilizer. India Patent Office; New Delhi, India: Jul 11. (Patent Application 2093/DEL/2013).
39. Zubarev ER. (2013). Nanoparticle synthesis: any way you want it. Nat Nanotechnol. ; 8:396–397.
40. Kalpana-Sastry R, Rashmi HB, Rao NH, Ilyas SM. (2009). Nanotechnology and Agriculture in India: The Second Green Revolution?; Presented at the OECD Conference on "Potential Environmental Benefits of Nanotechnology: Fostering Safe Innovation-Led Growth" Session 7. Agricultural Nanotechnology; Paris, France. July 15–17.
41. Nowack B, Bucheli TD. (2007).Review: occurrence, behavior and effects of nanoparticles in the environment. Environ Pollut. 150:5–22.