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Challenges and future prospects of agri-nanotechnology for sustainable agriculture in India

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HIGHLIGHTS

- Sustainable agriculture is necessary to face the challenges of global food demand.
- Agriculture remains the back-bone of the almost all the developing nations.
- DST in India has launched NSTT (Nano-Science and Technology Initiative).

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ABSTRACT

Nanotechnology presenting an inventive frontier in present day agricultural practices is expected to turn into a key force in future by contributing innovative applications. This new approach using nano-principles in agriculture has immense possibilities in handling the world wide challenges of environmental security and sustainability, food production, food safety, food security and global threats of climate change. Nanotechnology is very expansively used in contemporary fields of agriculture, food processing, and food protection, packing industry, dairy industry, packaging, transportation and quality control of agricultural products. It has enormous prospective in making agriculture more proficient and resourceful by using nanoparticles to improve the precision in delivering the nutrients to the specific part at a specific time. Use of nano- based agro-chemicals, ceramic devices, filters; lamination methods have great potential of making agriculture more organized and efficient by transforming the conventional agro-practices. Indian government is also supporting this by making plans to extend support for expansion and commercial applications and acceptance of nanotechnology by encouraging private sector investments and empowering partnerships in public and private sectors . Though nanostructures have enormous benefits in agri-sector, still their relevance and significance had not moved up- to practical field environment. The concerns related to the availability, synthesis, level of toxicity, health hazards, transportation challenges and incongruity of regulatory structure restrict the broad recognition and acceptance of adopting nanotechnology in agriculture. The present paper is an attempt to analyze and propose inputs in addressing the present and future possibilities, perspectives, applications and challenges of incorporating nanotechnology in agricultural sector with a focus on Indian perspective.

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1. Introduction

Nanotechnology endorsing interdisciplinary relevance is accepted as the 6th most comprehensive technology in this current era. The development of nanoscience and nanotechnology has contributed and provided new and exciting frontier to almost every area of application with reflective influence on human life (Linkov et al., 2011; Navrotsky, 2000). The diverse applications of this technology are remarkable being acknowledged in all the fields like medicines, textiles, construction, energy, food, electronics, cosmetics, defense, and agriculture (Sharon et al., 2010; Caruthers et al., 2007; Sabourin and Ayande, 2015). It is anticipated that the current pace of worldwide research and innovations in nanotechnology will make its market to reach up to 100 billion by the year 2020. (Research and Markets, 2015). At the same time it is also well recognized that nanotechnology has enormous probabilities in agricultural sector and can revolutionize it with the use of principles of nanotechnology. By the year 2050 world will have to deal with the testing task of feeding and nourishing **around 9.7 billion** people. The major concern in accomplishing this task is to find ways within boundaries of limited resources by using them judiciously. In this situation nanotechnology comes up with better choices for a variety of agricultural aspects and can help in improving productivity and efficiency of the agri-practices. The innovative nanotechniques have subsidized the agrimarket with almost 25% growth rate and it is predicted that the incorporation of nanoprinciples in agri sector would push the comprehensive worldwide economic growth to about 3trillion USD by 2020 (NCPI, 2011; NAAS Nanotechnology in Agriculture, 2013; McKee and Filser, 2016) Amid all the previous revolutions at different times, 1960's Green-revolution and induction of nanotechnology in current times have greatly influenced the agriculture sector (NAAS, 2013; Mukhopadhyay, 2014a). The amplified use of chemical pesticides and fertilizers in agricultural practices through and post the era of Green revolution had raised grave concerns linked to environmental sustainability issues and health risks. As a savior, to ensure the safety of environment and people the novel philosophy of using bio-friendly fertilizers and pesticides as a substitute to agrochemicals came into existence. However, this pro environment approach also brings in some key issues related to these ecofriendly substitutes such as poor service-life, field stability, requirement of high dosage for optimum effects in a certain area and their performance under varying and unpredictable changes in environment. It was reported by the researchers that incorporating nanobased formulations have shown to overcome the issues with bio-formulations, Khot et al. (2012), Nair et al. (2010), Mukhopadhyays (2014b) and can combat the worldwide challenges of food demand and supply, crop production, environmental sustainability, food-security and climate-change. Nanotechnology is contributing various nano-devices, nano-formulations and nano-ingredients to improve the agricultural practices such as nano-herbicides and pesticides for efficient herbs, pests and weed management and nano-fertilizers for proficient nutrient execution (Sodano and Verneau, 2014; Mishra et al., 2014; Lahive et al., 2016; Rabbani et al., 2016), nano-biosensors for detecting the on-site water level, moisture and nutrient content in soil. Hence we can say that, nano-technology would play a responsible role in agricultural sector by transforming the food demand and supply system through improving crop production with maintaining the ecological-sustainability, environmental-safety, and economic-stability (Ghormade et al., 2011; Banotra et al., 2017; Wang et al., 2016).

2. Why to use nanotechnology in agriculture

Agricultural world has to face a broad gamut of challenges of nutrient deficiency, stagnation in crop yield, decline of organic matter in soil, climatic changes, shrinking of cultivable land and water availability, resistance towards GMOs and scarcity of labor.

- The Indian agriculture is still suffering the soreness of exhaustion caused by the practices of green revolution. In the last 50 years, the consumption of fertilizers has exponentially amplified from 0.5 tons in 1960 to 23 million tons in 2008 which proportionate with around four times rise in the food-grain output. Even with the booming success in grain productivity, the stagnancy in the yield of certain crops is also observed as an outcome of decrease in organic content of soil because of uncontrolled fertilization (Sastry et al., 2011; Adhikari et al., 2016; Tarafdar et al., 2012a; Pandey and Tyagi, 2016; Conway and Barbie, 1988; Amundson et al., 2015; Klitzke et al., 2014).
- The current ratio for NPK fertilizers in India is maintained at 10:2.7:1 which is far more than the ideal ratio of 4:2:1? The imbalanced and excessive fertilization in India is rapidly worsening soil-health and is a matter of grave concern for the researchers.

• In order to accomplish a goal of producing 300 million-tons of food demand for feeding the escalating population of almost 1.5 billion up-to year 2025, the nation will need 45 million tons of grains beside the existing demand of around 23 million tons. The degree of multiple-nutrient drainage is continuously increasing with every passing year leading to a crop-deficit of almost 25%–30%. To maintain and sustain the soil health it is essential to use both organic and inorganic nutrients in a balanced way, but the subsidized rates of in-organics and decline in the availability of organics is making it very difficult to achieve (Huang et al., 2015; Kah and Hofmann, 2014; Solanki et al., 2015; Tyagi, 2016). Drastic changes in climatic conditions like frequent drought occurrence, melting of polar ice-cap, sharp rise in temperature, variable rainfall patterns, is an another reason to think of and get adapted to some alternate methods in agriculture sector.

3. Applications of nanotechnology in agricultural practices

The course of agriculture is unpredictable because of **its** dependence on variable natural components like weather, season, water, soil condition etc. Therefore the sensing, recording, manipulating and storing the reliable and precise data of all the biotic and a-biotic components is very much crucial to meet out the challenges of quality and quantity of food demand while maintaining the sustainability of the environment (Servin et al., 2015; Bhattacharyya et al., 2016). this task requires proportionate amalgamation of agriculture with electronics and mechanical techniques. Infusing nanotechnology in agriculture helps in achieving improved results. With the help of vigorous and portable in-situ nanotechnology guided sensing, monitoring, and analysis, farmers would be able to improve their farming outputs. Nano-particles act together with plants leading to various physiological and structural changes guided by the nature of Nano-particles. The delivery of nano-particles in safe dosages might facilitate plant-growth and crop productivity (Tarafdar et al., 2012b; Zabrieski et al., 2015; Alloway and Alloway, 2008). The interaction amid plants and nano-particles might be chemical in nature involving membrane transport action, active oxygen species construction, lipid per oxidation, ion-cell disorder and oxidative-breakage. Nano-particles have shown considerable manipulation in seed germination, growth and seed vigor. Nanomaterials have shown to be very much effective for the growth and germination in plants. The CNTs have the characteristics of regulating the seed-germination and plant-growth. The multiwall CNTs have shown to augment the growth-rate in tobacco-cell culture by 55%–64% when used at low concentrations (Gottschalk et al., 2015; Suresh et al., 2013; Vijaya Shanti et al., 2011; Khodakovskaya et al., 2012) whereas at higher concentration it inhibits the rate of cellular-growth.

4. Nano-fertilizers and nano-sensors in agriculture

Nano-fertilizers have the potential to effortlessly break-through into seeds and boost the nutrient availability and accessibility to the growing seed-ling resulting into the improved root and shoot length when used in optimum concentrations. Use of nano-fertilizers improves the access and reach of nutrients to plant branches and leaves which in-turn gets reflected in the form of improved growth, quality and yield of vegetation (Adhikari et al., 2010; Stamp and Viser, 2012). Recently a new concept based on the combinations of tera-bit capacity, ultra-high density, high data rate and small form factor is being introduced in data storage. This scanning concept is being named as Millipede and is a very good scanning device for agriculture. Development of nano sensors is another remarkable development which contributes towards monitoring and data collection and management about soil and plant health (Rai et al., 2012; Khandelwal and Joshi, 2018). Numerous devices based on nano-principles are potentially being used as sensors in agricultural practices. CNT devices have the characteristic properties of precise sensing, diagnosis and drug-delivery for pest control and in live-stock health management. Carbon nanotube devices have shown potential property as biosensors, equivalent to biomolecules, like DNA and are useful for electrical sensing in extreme and critical bio-conditions. Nanomaterials are also been proved to be useful for controlled release and dosage management of nutrients and medicines for plants and livestock (De La Torre-Roche et al., 2013; Pérez-de-Luque and Rubiales, 2009).

5. Nanoparticle harvesting

Plants can be used as a medium for harvesting nanoparticles for industrial purposes. For this plants are being grown in specifically prepared and structured soil rich in specific particles, which the plants absorb. These particles are then mechanically extracted from the plants. The biological route of synthesizing metal nano-particles (gold, silver, copper, zinc, palladium, platinum) (Mathhew et al., 2006; Quintanar-Guerrero et al., 1998; Xu et al., 2015) by using plants body parts, inactivated tissues and plant extracts has garnered much interest as an appropriate substitute to physical and chemical methods of synthesis. Bio-synthesis of metalNPs by plant extracts is economically effective and environment friendly alternative for producing metal nanoparticles on large scale. Bio-molecules from plant extracts like amino-acids, saccharides, plant proteins, enzymes, organic-acids function as capping agent and as reducing agent for metal NPs (Beyrouthya and Azzia, 2014; Tourinho et al., 2015; Wakelin et al., 2014; Prasad et al., 2014). Most of the bioroutes of synthesis are still in their developmental stage, struggling with the issues of controlling the extent of crystal growth, size-distribution, stability and separation and extraction of NPs (Khursheed Ahmad Wani and Kothari, 2018; Giongo et al., 2016; Perlatti et al., 2013).

6. Nanorobots

Nano robots along with high-speed wire-less connection have the power to explore the fine capillaries of plants through scanning (Wilson et al., 2008; Vandana et al., 2011; Vigani and Rodríguez-Cerezo, 2015) and communicating the details and are being used for fine inspections and analysis in farm diagnostics.

7. Nanotechnology and food industry

In addition to agriculture nanotechnology has vast applications in food industry which ranges from packaging and preservation to smart delivery. Infusion of nanotechnology into interactive food creation and preservation lets consumers' modify and transform their food as per their own taste and nutritional requirements (Chen and Yada, 2011; Cui et al., 2010; Singh et al., 2017). Nano-composites when used for food packaging improve the preservation and shelf-life of the food by incorporating antimicrobial agents on the surface. They also have the potential to enhance the resistance towards thermal and mechanical stress and decrease the transmission rate of oxygen in plants. Nanocapsules (Katouzian and Jafari, 2016; Grillo et al., 2016; De Oliveira et al., 2014) loaded with specific nutrients like vitamins, color and taste enhancers when added to food act dormant and give sustained release as per the requirement of the body (Vauthier and Bouchemal, 2009; WHO, 2015).

8. Indian perspective of nano-agriculture

Agriculture remains the back-bone and support system of the almost all of the developing nations. **It not only feeds the people** but also fuels and strengthens the economy. India has largest cultivable area for rice, cotton and wheat. With the limitations of water and land resources it is being assured by the policy-makers to maintain agriculture growth rate of around 4%. To achieve and maintain this growth rate a continuous flow of innovative technologies into agriculture sector is very much essential (Schlich et al., 2013; Roco, 2003; Bakry et al., 2016). As per censuses 2014–2015, India has a reported population of around 1.27 billions and to feed such a mammoth population it is the need of the hour to adopt new technologies resulting into increased yield in very short time (Agarwal et al., 2015; Ditta, 2012). The Government is working towards encouraging applications of nanotechnology for boosting productivity rate in Indian agriculture. In recent times, Planning-Commission of India has recommended R&D in nanotechnology as one of the six identified areas for investments (Vandana et al., 2011). The financial planning report of the commission was integrated into eleventh 5-year plan of India. Under this, government plans to establish National Institute of Nanotechnology in Agriculture to exploit the advantages of nano-technology, to renovate Indian agriculture. As per the report of the commission nanoparticles like nanobarcodes, nanosensors, nano based drug delivery can help in efficient usages of water, pesticides and fertilizers (Dey et al., 2017) in Indian agriculture. It is recommended in the report that educational institutions should train young graduates in nano-technology. This vision necessitates inclusion of technologies increasing productivity rate and product-quality, trimming down on-farm expenditure and increasing returns with conserving and enhancing environment and natural resources sustainably (Kah, 2015; The Changing Pattern, 0000). Achieving this objective would require a diligent effort to create a system to establish and market these innovations based on nanotechnology. To felicitate this vision DST (Department of Science and Technology), in the year 2001 has launched NSTT (Nano-Science and Technology Initiative) under the headship of Prof. C.N.R. Rao. This initiative by DST has its focus on making India an important contributor in the development of nanoscience through research and practical applications (Subramanian and Rahale, 2009; Chaudhary and Misra, 2017). Under the eleventh 5-year plan Indian Government is presently contributing a budget of ∼thousand cores under the Nano-Mission. The objectives of Nano-Mission cover various programs for research and development, promoting partnerships between private and public sectors, launching HRD and education programs, encouraging entrepreneurs, etc. Even after all these efforts nano applications in Indian agriculture is still in its primitive stage and needs to researched on vigorously (Mishra et al., 2017; Biswas and Sharmas, 2008).

9. Assessment of role of nanotechnology in India

It is a difficult task to assess the role of budding techniques like nanotechnology in developing countries like India and China, because of the non-availability of authentic historical information and most of the work being done is still in its primitive stage in patents and publications with commitments of further research (Kostoff et al., 2007; Sastry et al., 2010) The detailed studies of patents, research publications help in the assessment of developments in the use of nanotechnology in agriculture. A systematic framework of patents and bibliometrics was designed to assess the potentials of nanotechnology for improvements in Indian food security systems.

i. Mapping of nanotechnology contribution for all the sections of Indian agriculture including all the pre and post harvest steps involved.
ii. Mapping of nanotechnology contribution for all the dimensions of food security from soil, water, food and health.

The study of these pre-pared documents makes the assessment of growth of nanotechnology in different quarters of agriculture.

9.1. Regulatory policies and considerations

The biggest challenge in-front of the policy-makers is of commanding an area where most of the information is still under research or unknown. In these circumstances, overregulation may retard advancements, while, under regulation might lead to unfavorable health-effects. Irrespective of all the encouraging progress of nanotechnology in diverse areas, its applications in agri-sector still do not congregate the global-needs, because of the superficial consciousness and associated safety-concerns (Meyer et al., 2009; Kumar, 2015). The primary cause for the dearth of commercialization of agri-nanotechnology is because of the inadequate regulatory strategies, legislative-framework, and unconstructive civic opinions. Consequently, it is very much necessary to meticulously review the risk-assessment and risk-management aspects linked with the applications of nanotechnology in agri-sector, before implementing dictatorial plans (WHO, 2015; EPA, 2012; Engeman et al., 2012). In this regard, numerous regulatory organizations like Nanotechnology Initiative Division, DIT, Ministry of Law and Justice, CDC (Centre for Disease Control and Prevention), CKMNT (Center for Knowledge Management of Nanoscience and Technology) etc. and a range of principles are being adopted by nations to regulate the use and effects of nanotechnology in food, feed and agri-sectors. It is the Registration, Evaluation, Authorization and Restriction of Chemicals, REACH which primarily discusses different aspects of using nanoparticles in food-additives and supplements, plant-protection-products and food-contact materials (OECD/FAO, 2016; Eu, 2011). It is very significant to notice that it is the ambiguity in regulatory structures and disparity of opinion all over the world, which is restricting the flourishing and marketing of nano-based products made for agri-sector (Dimkpa, 2014). Sharing the opinions and views related to risk-assessment and management, globally would help in taking proficient regulatory measures (Mohan et al., 2012; Mills, 2013). A study of Indian researchers operating in the areas of nano-research illustrated that around 95% of them have identified the problems related to the ethical and moral-issues in all the fields of nano-research. Few of the identified concerns speak about the unfavorable effect of nanotech-research on human and environmental health, their exploitation as untraceable weapons in war, and integration of new nano-devices in humans as performance-enhancers (Agrawal and Rathore, 2014; Amenta et al., 2015; Handford et al., 2015). One of the reasons for the lack of debates on ethical-issues, safety concerns, health risks and environmental apprehensions about new technology might be the illustrious rank which the science-practitioners avail in India and policy-makers splurge a large amount of focus celebrating the accomplishments of science than talking about the hazards connected with a new technology and making improvements in regulation systems (Prasad et al., 2017). It is because of the lacuna in regulatory system that chemicals like nano-insecticides are being traded in Indian markets without any risk assessments (NAAS Nanotechnology in Agriculture, 2013; Biswas and Sharmas, 2008). This all is being practiced regardless of the acknowledgment by Indian government that the nanoparticles of the size analogous to human-cell can get accumulated in the lungs damaging it directly or by getting trans-located to new body parts or they may get absorbed by the body all the way through blood. Recently, in order to deal with such issues DST has released a set of precautionary and procedural guidelines for the safe and secure management of nanomaterials in industries and research-laboratories (Patil et al., 2016). This effort by DST is a potential step for a safer future of nanotechnology various sectors in India. The apprehension related to safety issues with nanomaterials has made The Nano-Mission to take a step to plan a dictatorial skeleton to manage the concerns related to EH&S (Environment Health and Safety) effect and dangers associated with nanoproducts. In recent times a team has been made in the supervision of ex-director IGCAR (Indira Gandhi Center for atomic research), Dr. Baldev Raj to design a framework for regulating the use of nanotechnology in country (Chaudhary and Misra, 2017). Following the guidelines of this team the Centre for Knowledge Management of Nanoscience and Technology and International Advanced Research Centre for Powder Metallurgy & New Materials is designing a set of regulatory principles for industry, research and technologists to execute the safe and sound management of nanomaterials.

9.2. Future of agriculture- nano-bio-farming

The materials for agriculture are being selected depending on their biocompatibility, bio-degradability, cost effectivity and nontoxicity (Auffan et al., 2009). It is predicted that the developments in agri-nanotechnology will promote the concept of precision farming promoting and permitting the judicial use of natural resources for agricultural practices (Duhan et al., 2017; Liu and Lal, 2015; Dikshit et al., 2013). The green synthesis of nanoparticles using plant extracts and microbes is a boon for safe and advance research in agri-nanotechnology. Nanomaterials play a significant role in crop protection by targeting plant–pathogen interactions through high amount of energy altercations (Singh et al., 2016; Wilson et al., 2008). The large surface area of nanoparticles makes them advantageous for the sustained release of fertilizers to the soil. This makes the use of nano-coated fertilizers, herbicides, fungicides, pesticides to improve their release and surface protection (Oliveira et al., 2015; Durán and Marcato, 2013). The nano-coating on fertilizers reduces the dissolution-rate which leads to slow and controlled release of fertilizers to be absorbed by the roots of the plants. Nanocoated phosphate, urea help meeting the N_2 demand of the soil in India. Sulphur nanocoated fertilizer (Kumar et al., 2014; Tourinho et al., 2016), Kaolin nanoparticles (Shahid et al., 2016; Gogos et al., 2012). Nano-silver encapsulated nanofertilizers have shown to improve the strength of roots and seed growth. Chitosan nanoparticles, synthesized from PMMA, have the characteristics of controlled release of N, P and K fertilizers (Hasaneen et al., 2014; Corradini et al., 2010). Nanoparticles when coated on biofertilizers help overcome with the issues of their restricted shelf-life, thermal sensitivity and storage related problems. Gold and Silver nanoparticles when used with biofertilizers like Bacillus subtilis, Pseudomonas fluorescence and Paemibacillus elgi have given promising results of improved growth rate in plants (Wu et al., 2017; Maruyama et al., 2016). Gold nanoparticles can

Agri Nanotechnology Precision agriculture	Monitoring soil health	Nanosensors
	Controlling the release of agro-chemicals	Sustained release through nanoencapsulation
	disease management	Nanopesticides, Nanoherbicides
	regulating the plant growth	Nanobiofertilizers
	Water retention	Nanoclay
	Quality enhancement	Nano-assisted release of genetic-material for quality upgrading

Fig. 1. Agri-nanotechnology for precision farming.

be used as biofertilizer to promote plant-growth-promoting bacteria Rhizobacteria (Liu et al., 2012; Shukla et al., 2015). Nanotechnology is useful in making the availability of nutrients by using their nanoformulations as sprays on plants or in soil to improve soil vigor and health. Chitosan nanoparticles have shown positive effect on the release of plant growth hormone, 1-naphthylacetic acid (Thakur et al., 2018; Saharan et al., 2013; Silva et al., 2011; Abdel-Aziz et al., 2016). Spraying of FeO nanoparticles have shown to improve yield, protein content and spike-weight in wheat and work as a source of Fe for soybean plants. Thus integration of nanotechnology in agriculture offers an efficient mode of sensing, detection and bio-remediation along with enhancing the agriculture yield through -i) controlled and efficient release of water and nutrients by using Nanoporous-zeolites. (ii) sustained delivery of herbicide, pesticides and insecticide by using Nano-capsules (iii) detecting toxins, pests and monitoring environmental conditions by using Nanosensors (iv) using nanoparticles in various processes as photocatalysts Fig. 1 (Szakal et al., 2014; Gupta et al., 2015)

10. Conclusion

India is an agrarian economy but the rate of agricultural growth is going through a rough phase and needs a serious boost to improve productivity and nanotechnology comes in rescue and helps in improving the productivity. Nanotechnology has both off-site and on-site applications in agriculture and Indian scientists and analysts are focusing on research and development activities through education to invent and adapt nano-applications to suit socio economic environment of India. The acceptance of nanotechnology depends on their environmental effects, safety concerns, health hazards and their social implications. Still there is a long way to go in understanding their health and safety risks for the researchers and consumers and further research is needed to analyze that. The enhanced surface area of nanomaterials might bring in toxic effects, not evident in bulk therefore future research in agri nanotechnology should stress in the direction of assessing and overcoming the risk issues related to the use of nanoparticles. The studies on the synthesis and their applications are still restricted to laboratory level and are not contributing towards the broad recognition and acceptance of nanotechnology in agri-sector. Therefore scientific fraternity have to put efforts to improve the researches by adapting the more practical and realistic approaches. Validation of the permissible dosages of nanoparticles within the safety limits along with their trans-generational effects is required to be investigated and elucidated. This task possibly will be accomplished through the concentration dependent studies in soil systems to comprehend the correct and safe dosage of nanoparticles for farming. Further studies are required towards effective soil-management to improve soil environment might support the efforts to reduce toxic effects of nanoparticles resulting into considerable encouraging influence in agro-ecosystem. Lastly, and most significantly, I sturdily advocate the inclusion of biosynthesis of nanoparticles as a prerequisite for exhaustive research practices. Biosynthesis of nanoparticles using green-synthesis might have comparatively less or no toxicity. The present scenario of nanotechnology in India is not very inspiring and Indian agriculturists need further communication, information, guidance and counseling to understand and adopt nanosolutions.

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