



A review on application of nanotechnology for sustainable agriculture: The future of farming

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Abstract

The objective of sustainable agriculture is to meet society's food and textile necessities without negotiating the ability of future generations to meet their own needs. The limited natural resources and increasing population rate is the biggest challenge in the present era for scientists to fulfill global agricultural demand in sustainable manner. The widespread use of chemical fertilizers and pesticides to provide food security to the ever-expanding population has toxic effects on the soil, environment and human health. Therefore, it is essential to adopt sustainable agriculture practices that can enhance crop production without the excessive use of fertilizers and pesticides.

Recent advances in synthesis and functionalization of nanoparticles have brought a significant increase in agricultural applications and received significant attention in agrochemical field as it naturally overcomes the defects of conventional agrochemicals. Nanofertilizers and nanopesticides are the most promising solutions for conventional fertilizers and pesticides. Nanotechnology has the prospective to improve the agriculture and food industry with novel nanotools.

This review paper emphasizes recent advances in nanotechnology and its safe application in agriculture. The potential uses and benefits of nanoparticle-based fertilizers and pesticides have also been discussed.

Keywords: Nanotechnology, sustainable agriculture, nanofertilizers, nanopesticides, nanobiosensors

Introduction

Agriculture is worldwide the most significant and stable sector of the economy because it satisfies human food and fiber needs, both directly and indirectly. Nowadays, agriculture is facing challenges such as rapidly increasing population rate which is assumed to be about six billion by 2050^[1], reduced productivity of crops due to biotic and abiotic stresses^[2], water scarcity^[3], deforestation^[4] and climate change^[5]. In agriculture sector fertilizers are regularly used for plant growth and productivity^[6]. Rapid mechanization, development of new technologies as marker-assisted breeding and transgenic crop production, tremendously increases the crop productivity^[7]. Although these practices increase the crop production but they exert many deleterious effects on the soil, environment and human health^[8].

Concept of sustainable agriculture provides a possible solution to empower agriculture systems to feed a growing population within the altering environmental conditions^[9]. Sustainable agriculture embraces a wide range of techniques, including organic farming, free-range, low-input, holistic, and biodynamic. "Healthy" soil is an important component of sustainability. Methods to enhance and protect the productivity of the soil include using cover crops, compost/manures, avoiding traffic on wet soils, and maintaining soil cover with plants/mulches.

It is presumed that the global food consumption is likely to increase from 59% to 98% by 2050^[10]. It is the biggest challenge to ensure food security for such a vast global population. Among much scientific advancement, potentiality of nanotechnology has been proved for reviving the agriculture industry^[11]. Today, nanotechnology impacts every aspect of the agriculture field from cultivation to packaging^[12] and has exclusive applications in agriculture research^[13]. The usage of nanomodified tools and technologies can accelerate current efforts for sustainable agriculture developments.

Fundamentals of nanotechnology

The term nanotechnology has been coined by Norio Taniguchi and the concept was presented by Dr. Richard Feynman^[14]. It is defined as the science of understanding and control of matter at dimensions of roughly 1-100nm, where unique physical properties make novel applications possible^[15]. It aims the designing of tools and systems at nanometer level^[16] and manipulate matter at the atomic level^[17]. The importance of nanotechnology is not only due to the miniature size of nanomaterials but also having capacity to control the physical, chemical, biological, physiochemical and mechanical properties of matter operating at nanoscale^[18]. Entirely different properties of materials at nanoscale provides more strength, improved optical properties, modified antimicrobial potential and outstanding superconductive nature to nanomaterials^[19]. Due to these upgraded properties nanotechnology has the potential to revolutionize various fields that influence human life^[20]. Intense research investigations are focusing on increasing the application of nanotechnology in agriculture sector^[21]. Today nanotechnology is one of the promising areas to improve the agricultural production system with less adverse environmental impact^[22].

Nanotechnology and sustainable agriculture development

Nanotechnology is an interesting new area of research and technology development at nanoscale, having broad applications in agriculture science. Nanotechnologies have tremendous potential to improve agricultural practices in sustainable manner and develop applications for nanofertilizers and nanopesticides^[23]. If this technology is precisely introduced in plant breeding it can increase crop productivity through control of nutrients^[24], which directly increases global food security^[25]. It can also participate in the monitoring of water quality and pesticides for sustainable agriculture development^[26]. Nanoparticles have recently received attention due to low toxicity and greener

approach [27] in plant disease control and agriculture development [28]. Nanomaterials not only catalyze degradation of waste and toxic materials but also improve the efficiency of microorganism in degradation of waste and toxic material sustainably [29].

Use of nanobiotechnology in agriculture eventually helps to enhance the yield and nutritional value of crops [30]. This technology ultimately contributes to enhance the quality and quantity of plant production, main emphasis of every breeding program [31].

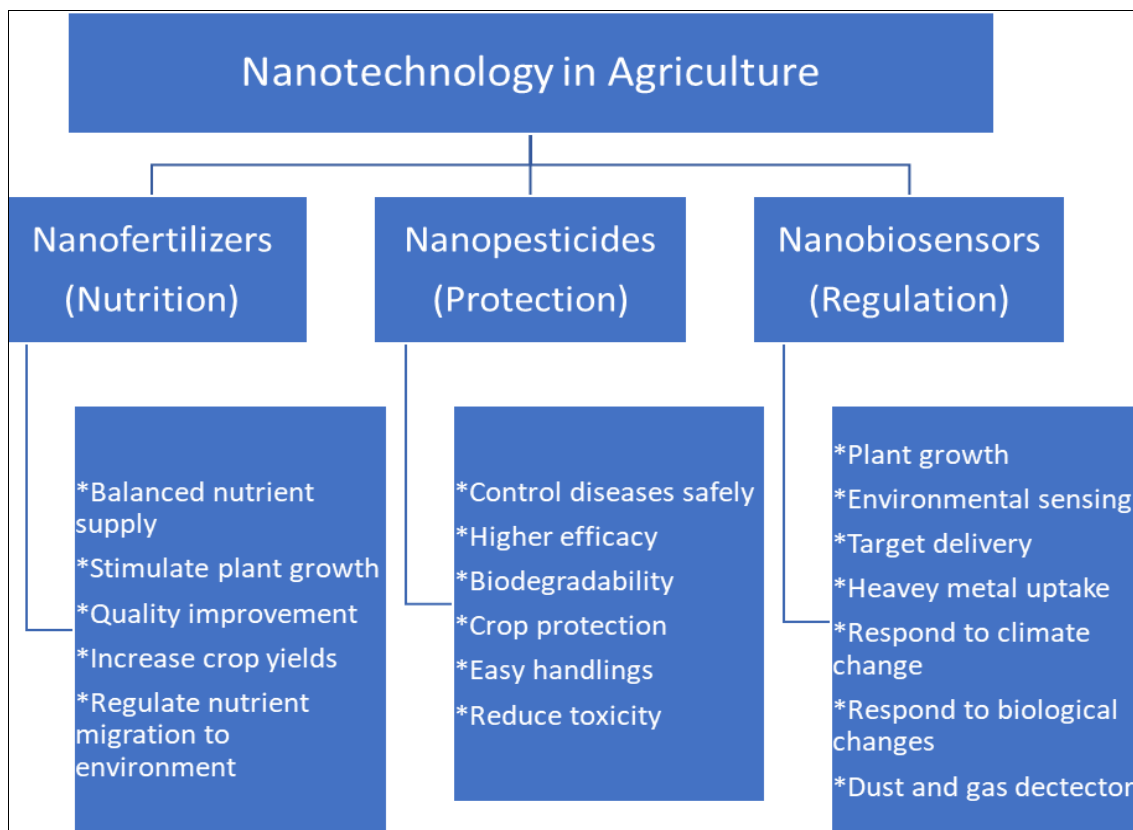
Sustainable agriculture is the key for existence of mankind in the future era, which involves the strategy to make the agriculture system self-sustaining for a long period. Thus use of nanotechnology provides a secure method for

sustainable agriculture development [32]. Today, a wide range of potential applications of nanotechnology has been visualized in agriculture, which leads to intense research at both academic and industrial levels [33].

Potential of nanotechnology in sustainable agriculture

Nanotechnology have received appreciable attention in the agrochemical field due to its miniature dimension. It has the potential to maintain the sustainability of agricultural systems and improve crop productivity by the use of nano fertilizers, nano pesticides and nano sensors. Schematic representation of applications of nanotechnology in agriculture is depicted in Fig 1.

Fig 1: Schematic representation of applications of nanotechnology in agriculture



Nanopesticides

Pesticides play a crucial role in pest management and promote crop productivity [34]. Nanopesticides have potential to achieve greater effects with lower chemical dose in ecofriendly manner. Active ingredients of nanopesticides are either metal (Ag, Cu) nanoparticles [35] or metal oxides (ZnO, CuO) nanoparticles [36]. Nanomaterials used in nanopesticide formulation improves the bioavailability of active ingredients [37]. In current scenario, nanopesticide formulation has slow releasing properties with enhanced solubility, permeability and stability [38], which actively defined against biological disaster and promote crop

productivity in ecofriendly manner [39]. Nanomaterials used in pesticide production participate in establishing formulation systems to decrease the toxicity of pesticides to the non-targets and improve the bioavailability of active ingredients to the applicable area. Some nanomaterials could be directly used as nanopesticides due to their antibacterial, anticandidal and antifungal activities [40]. Now a days use of nanopesticides have received lots of attention due to boom in organic farming and increased awareness of environmental protection [41]. List of nanopesticides biopesticides and their applications is summarized in Table 1.

Table 1: List of nanopesticides / biopesticides and their applications

| Carrier system | Active Ingredients | Function |
|---|-----------------------|--|
| Chitosan | Imazapic and Imazapyr | Lower cytotoxicity |
| Alginate | Imidacloprid | Lower cytotoxicity, sucking pest |
| Polyacetic acid-polyethylene Glycol-polyacetic acid | Imidacloprid | Decrease the lethal concentration |
| Carboxymethyl chitosan | Methomyl | Control release for longer time period |
| Chitosan tripolyphosphate | Paraquat | Lower cytotoxicity and genotoxicity |

| | | |
|--|------------------------------|---|
| Chitosan-Cu | CuSO ₄ | Antifungal activity |
| Wheat gluten | Ethofumesate | Reduce diffusivity |
| Alginate | Azadirachtin | Slower release |
| Surfactants/oil/water | Glyphosate | Increase in bio-efficacy |
| Alginate-chitosan | Paraquat | Reduce ecological toxicity |
| Polyhydroxybutyrate-co-hydroxyvalerate | Atrazine | Decrease genotoxicity and increase biodegradability |
| Organic-inorganic nanohybrid | 2,4-Dichlorophenoxyacetate | Control release |
| Nanotubular sodium titanate | Bacillus thuringiensis | Effective in controlling cotton leaf worm |
| Silica nanoparticles and carbon fibers | Beauveria bassiana | Improve mortality to larvae of potato Spodoptera litura |
| Chitosan coated nanosilver | Essential oils | Synergistic effect against various microorganisms |
| Polyethylene glycol-carboxymethyl cellulose | Avermectin | Increase the biocompatibility of Avermectin |
| Polylactic acid | Validamycin and thifluzamide | Better control of rice sheath blight |
| Layered double hydroxides | Gibberellic acid | Promote plant growth |
| Chitosan encapsulated zinc oxide nanocomposite | Chitosan and zinc oxide | Improve agronomic traits of crops |

Nano fertilizers

Industrial agriculture requires the frequent use of fertilizers to boost the crop yield and productivity. Presently chemical fertilizers are most liked by farmers, as they are effective and economically cheaper than other fertilizers [42]. Continuous use of chemical fertilizers plays a detrimental effect on both the human health and environment. Extensive research in the field of nanofertilizers / biofertilizers and soil health has been done since last decade to minimize the harmful effects of chemical fertilizers. Organic fertilizers are better substitute for chemical fertilizers as it improves the soil texture, holds water for longer period and is more ecofriendly. The main disadvantage associated to organic fertilizers, is the gradual release of nutrients. Several microorganisms act as natural fertilizers, known as biofertilizers [43]. Biofertilizers provides essential nutrients to

the soil, required for plant growth and productivity in sustainable manner. Besides increasing soil nutrients, these microorganisms also produce bioactive compounds, antagonistic compounds and organic acids.

Nanofertilizers are nanostructured formulations that slowly release active ingredients into the soil in the controlled manner [44]. Due to their higher efficacy, performance and availability nanofertilizers are good choice for sustainable nutrient delivery systems [45] in comparison to chemical fertilizers. Formulation of nanofertilizers restores soil fertility, reduces soil toxicity, increases plant health and production [46] in ecofriendly manner [47]. Nanotechnology have acquired great importance in agribusiness to upgrade agricultural practices by using nanofertilizers [48]. Some nanomaterials that act as potential nanofertilizers and their applications are summarized in Table 2.

Table 2: List of nanofertilizers and their applications

| Nanomaterials | Plants | Applications |
|--------------------------------|-------------------------|---|
| AgNPs | Vigna unguiculata | Growth inhibition of harmful bacteria |
| SiO ₂ | Oryza sativa | Cd translocation inhibition |
| SiO ₂ | Tomato | Enhance seed germination |
| SiO ₂ | Cucumber | Increase plant height |
| TiO ₂ | Barley | Increase vegetative growth |
| TiO ₂ | Tomato | Increase vegetative growth |
| TiO ₂ | Vigna radiata | Increase chlorophyll content |
| ZnO | Cyamopsis tetragonoloba | Enhances growth physiology |
| ZnO | Coffea arabica | Acceleration of photosynthesis |
| ZnO | Tomato | Increase root and shoot length |
| ZnO | Lactuca sativa | Increase photosynthetic rate |
| ZnO | Mungbean | Increase plant height |
| CuO | Tomato | Increase sugar content |
| CuO | Zea mays | Enhance maize growth |
| Au | Cucumber | Enhance root growth |
| Carbon | Soybean | Enhance cell growth |
| CeO ₂ | Raphanus sativus | Increase chlorophyll content |
| CeO ₂ | Tomato | Improve yield |
| Fe ₂ O ₃ | Spinach | Increase plant biomass |
| Fe ₂ O ₃ | Arachis hypogaea | Increase growth |
| Fe ₂ O ₃ | Rice | Enhance root elongation |
| FeS | Mustard | Improve yield |
| Ag | Fenugreek | Promote plant growth |
| N | Rice | Improve yield |
| P | Cotton | Increase growth |
| Al ₂ O ₃ | Solanum lycopersicum | Counteract Fusarium as a biocontrol agent |
| N, P and NPK NPs | Triticum aestivum | Significant changes in plant growth |
| NPK NPs | Wheat grains | Increase in saccharide content |
| Zn and B NPs | Punica granatum | Increase in yield |
| Zn, Fe and NPK | Chickpea | Increase in biological output |
| MnO | Vigna radiata | Improve metabolism |
| MgO | Clusterbean | Increase chlorophyll |

Nano biosensors

In present era, nanotechnology is widely used in the development of biosensors. In agriculture, nanomaterial-based biosensors are being used as a rapid detection tool. Scientists believe that nanobiosensors can play a crucial role in revolutionizing the farming system by detecting the nutrient levels in soil and crops, detecting and diagnosing pathogens, monitoring plant growth and environmental

stresses [49]. Due to special properties of nanomaterials, nanobiosensors have high sensitivity and selectivity, quick reliable results and ability to detect smaller quantities. These biosensors are also capable to detect, respond to the physiochemical and biological changes in crops and mycotoxins present in various foods. Nanomaterials used in various biosensors and their role in agriculture is listed in table 3.

Table 3: List of nanomaterials used in nanobiosensors and their applications in agriculture

| Nanomaterials used | Application |
|--|---|
| Carbon nanotubes | Detection of methyl parathion |
| Nanogold | Detection of karnal bunt disease in wheat |
| TiO ₂ nanotubes | Detection of atrazine concentration in the soil |
| Gold nanoparticles with acetamiprid binding | Detection of acetamiprid |
| Graphite electrode | Detection of glyphosate and glufosinate |
| Acetyl cholinesterase | Detection of organophosphates pesticides |
| Acetyl cholinesterase with hollow gold nanospheres | Detection of chlorpyrifos and carbofuran |
| Cysteamine modified gold nanoparticles | Detection of water nitrate content |
| Au nanoparticles | Detection of urea and inhibition of urease |
| Quantum dot-FRET | Detection of Polymyxabetae, vector of beet necrotic yellow vein virus |
| ZnO nanoparticles | Detection of Trichoderma harzianum in the soil |
| Nanocantilevers | Detection of microbes and toxins |
| Zinc oxide and copper | Enhance germination of tomato in Mexico |
| Carbon nanomaterial | Detection of aflatoxins in peanut and rice |
| Receptor DAD2 with protein | Detection of strigolactones for plant growth |
| Carbon nanotubes | Detection of heavy metals as Cu, As, Hg |
| Acetylcholinesterase with indophenol acetate | Detection of chlorpyrifos |
| DNA based biosensor | Detection of phytophthora palmivora |
| Carbon dots | Detection of kaempferol polyphenol |
| Cholinergic enzyme | Detection of malathion |
| Acetylcholinesterase with silver | Detection of malathion |
| Multiwalled carbon nanotubes | Detection of Mosaic virus |
| Calcium phosphate | Detection of pathogen |
| Cholinergic enzyme | Detection of dichlorvos |
| Graphene | Detection of pesticide |
| Acetylcholinesterase with carbon nanotubes | Detection of paraoxon |
| Carbon nanomaterials | Detection of pathogens |
| Cholinergic enzyme | Detection of chlorpyrifos |

Future perspectives of nanotechnology in agriculture

Nanotechnology has a potential to bring revolution in future of agriculture in the sustainable manner with possible environmental remediation. Engineered nanomaterials are capable for precise delivery of agrochemicals to improve disease resistance and plant growth [50]. It has a potential to provide novel and advanced solutions to enhance agricultural productivity with low cost and energy input.

However, despite the public acceptance, a critical assessment of the impact of nanoparticles is must before they are determined to be safe to use. Our current knowledge is not sufficient to predict the probable environmental impacts of nanoparticles. More care is required, in the synthesis and use of nanoparticles in agriculture sector, as the nanotoxicity studies are very limited and can cause potential risk to plants, microbes, animals and even humans. Thus, further research needs to proceed to evaluate the benefits and risks of nano agrochemicals in a reasonable manner.

Conclusion

Nanotechnology has potential to revolutionize the future of agribusiness because of its miniature dimension and wide-ranging applications. But the uncertainty issues of toxicity and safety associated with nanomaterials is a major risk factor for human health and environment. The nanotoxicity

studies in agriculture are confined. Thus, further research is needed before the wide spread use of nanomaterials in agriculture sector. Risk due to nanoparticles could be controlled by using greener synthesis and seeking for easy and economical process for degradation and removal of existing nanomaterial from the attacking sites.

Educational programs and research projects can provide platform to educate farmers about the use of nanotechnology in agrifields in a sustainable manner. Sustainable agriculture must be taken in an ecofriendly manner, where the biotic and abiotic beings maintain a coordinated stability of food chains and their related energy balances.

Lastly the introduction of reasonable policies and popularization of greener nanotechnology among the public and concerned figures (farmers) will be more beneficial to promote its development in sustainable manner.

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