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Perspectives for nano-biotechnology enabled protection and nutrition of plants

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ABSTRACT

Indiscriminate use of pesticides and fertilizers causes environmental pollution, emergence of agricultural pests and pathogens, and loss of biodiversity. Nanotechnology, by virtue of nanomaterial related properties, has potential agro-biotechnological applications for alleviation of these problems. The literature pertaining to the role of nanotechnology in plant and soil systems demonstrates that nanomaterials may assist in a) the controlled release of agrochemicals for nutrition and protection against pests and pathogens, b) delivery of genetic material, c) sensitive detection of plant disease and pollutants and d) protection and formation of soil structure. For instance, porous silica (15 nm) and biodegradable, polymeric chitosan (78 nm) nanoparticles displayed slow release of encapsulated pesticide and fertilizer, respectively. Further, nanosized gold (5–25 nm) delivered DNA to plant cells while iron oxide (30 nm) based nanosensors detected pesticides at minute levels. These functions assist the development of precision farming by minimizing pollution and maximizing the value of farming practice.

Contents

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1. Introduction

Conventionally, pathogens and pests are controlled by annual pesticide applications of ~2 million metric tons worldwide (worth US $ 35 billion), 90% of which are lost to the air during application and as run-off, affecting both the environment and application costs to the farmer (Stephenson, 2003). Indiscriminate pesticide usage increases pathogen and pest resistance, reduces soil biodiversity, diminishes nitrogen fixation; contributes to bioaccumulation of pesticides, pollinator decline and destroys habitat for birds (Tilman et al., 2002). Moreover, the application of excess volumes of fertilizers adds to the tribulations of the already delicate ecology as run-off (Tilman et al., 2002). The world demand for fertilizer was forecast to increase by 4.8% to 170.4 million metric tons by 2010/11 (Heffer and Prud'homme, 2010). Therefore there is an urgent need to tackle the excessive usage of pesticides and fertilizers by a) finding alternatives to current pesticide and fertilizer deployment, b) rapidly and locally detecting presence of pathogens and pests, as well as pesticides and nutrient levels; and c) developing methods for either agrochemical removal or degradation to promote soil health.

Biotechnological advancements in protection and nutrition strategies for plants have attempted to provide some solutions for these problems. Crop improvement for disease resistant or stress tolerant plants is one such approach. Transgenic insect resistant maize and cotton crops, with insecticidal genes from *Bacillus thuringiensis,* seek to replace insecticides with host-plant resistance that provides higher yields. However, transgenic crops are not accepted globally, yet. Other alternatives to agrochemicals are biopesticides and biofertilizers. Biopesticides, comprise living organisms or their derived products, are natural antagonists of pathogens and pests. Their key advantages include specificity, safety to mammals and other non-target organisms, environmental compatibility, applicability with chemical pesticides in integrated pest management and acceptance for organic agriculture. Similarly, biofertilizers comprise environment friendly microorganisms that supply or improve availability of nutrients to promote soil fertility and crop productivity. Biopesticides and biofertilizers are slowly gaining acceptance in terms of their applicability, efficiency and eco-friendly nature, though their on-field stability and shelf life are the major concerns. Other approaches for reducing agrochemical applications are development of monitoring systems for plant pathogens and agrochemicals that allow early intervention and optimum application. Also, biotechnology has sought to restore agro-chemically damaged soils with microorganisms or plants *i.e.* bioremediation or phytoremediation, respectively. Although these biotechnological advances are evident, the present picture that remains is that of a rapidly degrading and polluted ecosystem caused by prevailing practices. To tackle the situation we need to harness innovative approaches towards agriculture such as nanotechnology.

Nanotechnology, the process to generate, manipulate, and deploy nanomaterials, represents an area holding significant promise for the agricultural scenario (Table 1, Baruah and Dutta, 2009; Navrotsky, 2000; Kuzma, 2007). Nanotechnology employs nanoparticles (NPs) having one or more dimensions in the order of 100 nm or less (Auffan et al., 2009). Other authors refer to NPs as colloidal particulate systems with size ranging between 10 and 1000 nm (Nakache et al., 1999). Nanomaterials hold great promise regarding their application in plant protection and nutrition due to their size-dependent qualities, high surface-to-volume ratio and unique optical properties. A wide variety of materials are used to make NPs, such as metal oxides, ceramics, silicates, magnetic materials, semiconductor quantum dots (QDs),lipids, polymers, dendrimers and emulsions (Niemeyer and Doz, 2001; Oskam, 2006; Puoci et al., 2008). Polymers display controlled release of ingredients, a character useful for developing polymeric NPs as agrochemical carriers. Metal nanoparticles display size dependent properties such as magnetism (magnetic NPs), fluorescence (QDs) or photocatalytic degradation (metal oxide NPs) that have biotechnological applications in sensor development, agrochemical degradation and soil remediation (Table 1).

Table 1
Applications of nanotechnology in agriculture.

Application	Nanoparticles	Reference
Pesticide delivery		
Chemical		
Avermectin	Porous hollow silica (15 nm)	Li et al. 2007
Ethiprole or phenylpyrazole	Poly-caprolactone (135 nm)	Boehm et al., 2003
Gamma cyhalothrin	Solid lipid (300 nm)	Frederiksen et al. 2003
Tebucanazole/chlorothalonil	Polyvinylpyridine and polyvinylpyridine-co-styrene (100 nm)	Liu et al. 2001
Biopesticides		
Plant origin: nanosilica for insect control *Artemisia arborescens*	Nanosilica (3–5 nm)	Barik et al., 2008
essential oil encapsulation	Solid lipid (200–294 nm)	Lai et al. 2006
Microganisms: *Lagenidium giganteum* cells in emulsion	Silica (7–14 nm)	Vandergheynst et al., 2007
Microbial product: absorption of *Myrothrecium verrucaria* enzyme complex	Chitosan/kaolin (250–350 nm)	Ghormade et al.unpublished
Fertilizer delivery		
NPK controlled delivery	Nano-coating of sulfur (100 nm layer)	Wilson et al. 2008
	Chitosan (78 nm)	Corradini et al. 2010
Genetic material delivery		
DNA	Gold (10–15 nm)	Torney et al. 2007
	Gold (5–25 nm)	Vijayakumar et al. 2010
	Starch (50–100 nm)	Liu et al. 2008
Double stranded RNA	Chitosan (100–200 nm)	Zhang et al. 2010
Pesticide sensor		
Carbofuran/triazophos	Gold (40 nm)	Guo et al. 2009
DDT	Gold (30 nm)	Lisa et al. 2009
Dimethoate	Iron oxide (30 nm), zirconium oxide (31.5 nm)	Gan et al. 2010
Organophosphate	Zirconium oxide (50 nm)	Wang et al. 2009
Paraoxon	Silica (100–500 nm)	Ramanathan et al. 2009
	Carbon nanotubes	Joshi et al. 2005
Pyrethroid	Iron oxide (22 nm)	Kaushik et al., 2009
Pesticide degradation		
Lindane	Iron sulfide (200 nm)	Paknikar et al. 2005
Imidacloprid	Titanium oxide (30 nm)	Guan et al. 2008

Potential applications of nanotechnology in agriculture are: delivery of nanocides–pesticides encapsulated in nanomaterials for controlled release; stabilization of biopesticides with nanomaterials; slow release of nanomaterial assisted fertilizers, biofertilizers and micronutrients for efficient use; and field applications of agrochemicals, nanomaterials assisted delivery of genetic material for crop improvement (Fig. 1). Nanosensors for plant pathogen and pesticide detection, and NPs for soil conservation or remediation are other areas in agriculture that can benefit from nanotechnology (Fig. 1). Enzyme immobilization for nanobiosensor using nanomaterials involves the high value low volume application of enzymes (Kim et al., 2006). Usually costly, large enzyme volumes are required for biocontrol in agricultural fields that would be practical if spray applications combined high volume with low value. Cost-effectiveness of such biocontrol preparations can be achieved by immobilization of enzyme/inhibitors on nanostructures, providing large surface areas, to increase the effective concentration of the preparation. In this review, we focus on nanomaterial-based technologies and their existing and potential applications in plant protection and nutrition.