CellPress

Review

Nanotechnology: A New Opportunity in Plant Sciences

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The agronomic application of nanotechnology in plants (phytonanotechnology) has the potential to alter conventional plant production systems, allowing for the controlled release of agrochemicals (e.g., fertilizers, pesticides, and herbicides) and target-specific delivery of biomolecules (e.g., nucleotides, proteins, and activators). An improved understanding of the interactions between nanoparticles (NPs) and plant responses, including their uptake, localization, and activity, could revolutionize crop production through increased disease resistance, nutrient utilization, and crop yield. Herewith, we review potential applications of phytonanotechnology and the key processes involved in the delivery of NPs to plants. To ensure both the safe use and social acceptance of phytonanotechnology, the adverse effects, including the risks associated with the transfer of NPs through the food chain, are discussed.

Trends

The field of nanotechnology has great potential within plant sciences and plant production systems.

The agronomic application of nanotechnology has thus far received comparatively little interest relative to the application within human systems.

We review the potential applications and future opportunities of nanotechnology in plant sciences, thereby assisting in bridging the divide between human and agricultural nanotechnology.

The application of nanotechnology in plant sciences will benefit from the development of improved analytical techniques that enable the *in situ* analysis of NPs *in planta* with a low detection limit and high lateral resolution.

Regardless of the benefits of nanotechnology for plant sciences, the principle of 'safety-by-design' must be heeded to address community concerns about the potential adverse effects of novel engineered nanoparticles (ENPs) on ecological systems.

Nanotechnology and Plants

Engineered NPs (ENPs, see Glossary) have unique physicochemical properties (e.g., small surface area, atypical surface structure, enhanced reactivity, etc.) that differ distinctively from those of their molecular and bulk counterparts. These properties typically result from the small size, chemical composition, surface structure, stability, shape, and agglomeration of the **nanoparticles** (NPs) [1]. Given these unique properties, ENPs are used increasingly in a range of consumer and commercial products, including semiconductors, microelectronics, catalysts, everyday domestic products (e.g., cosmetics and sunscreens), and for drug delivery.

Numerous applications in nanomedicine and nanopharmacology have developed ENPs as smart delivery systems. Specifically, ENPs can be loaded with a drug or other active substance (Figure 1A,B) for delivery to target-specific sites within a living organism. Considerable research efforts have been made to investigate the potential applications of ENPs within human systems, including for targeted drug delivery, cancer therapy, and treatment for loss-of-function genetic diseases [2]. Although the same principles can be applied to plant systems, the application of **nanotechnology** in plant sciences and plant production systems (**phytonanotechnology**) has received comparatively little interest thus far.

Phytonanotechnology could assist the development of 'smart' crops. Nanoscale materials can provide time-controlled, target-specific, programmed, self-regulated, and multifunctional capabilities [3]. For example, ENPs can deliver agrochemicals (e.g., fertilizers, pesticides, and herbicides) in an 'on-demand' manner, either for nutritional demand or protection against pests and pathogens. This provides an efficient way to avoid repeated applications of conventional agrochemicals and reduces adverse effects on plants and the environment. Additionally, the NP-mediated targeted delivery of nucleotides, proteins, and other phytoactive

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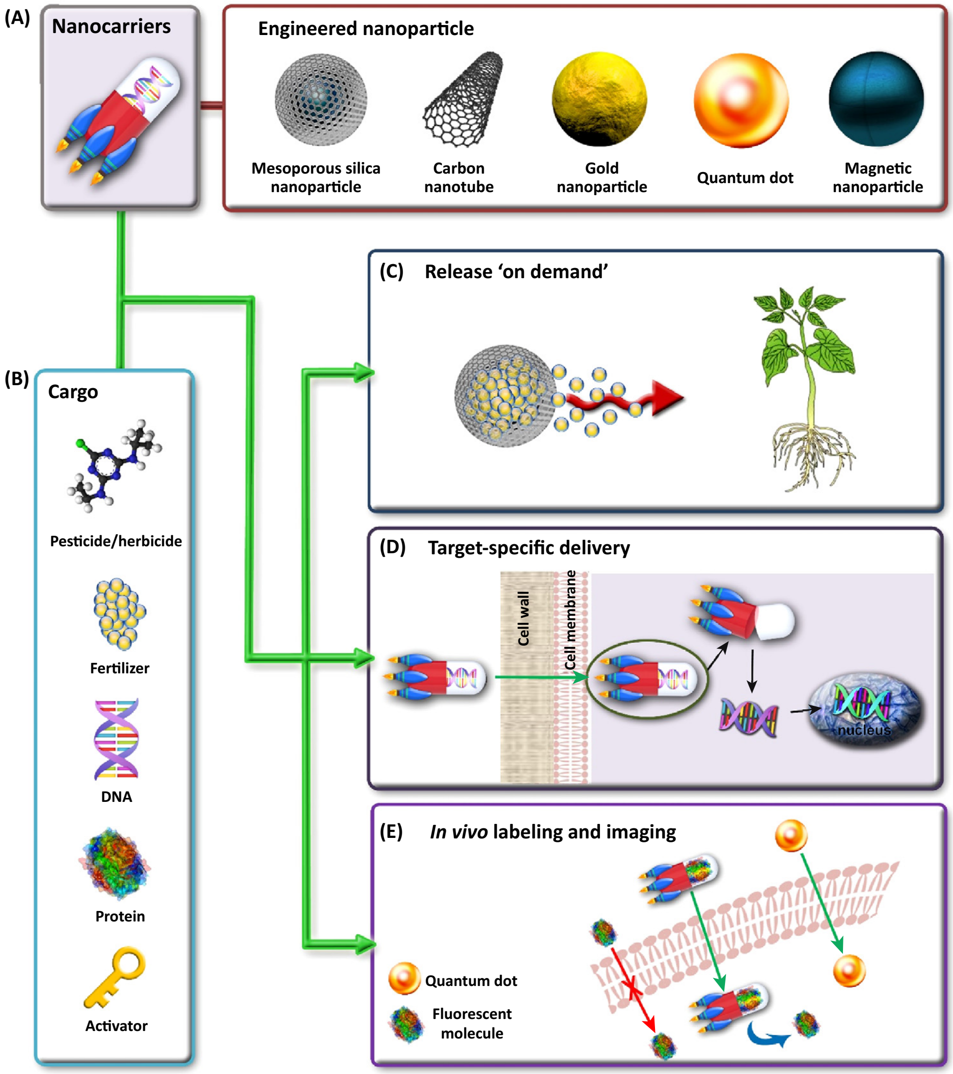

Trends in Plant Science

Figure 1. Schematic Representation of the Applications of Nanotechnology in Plant Sciences. (A) Engineering nanoparticles used as nanocarriers for delivery of various exogenous cargos (B), including agrochemicals and bioactive molecules. (C) Nanocarrier-mediated release of agrochemicals in a controlled manner. (D) Nanocarrier-mediated delivery of bioactive molecules into plant cells. (E) Nanocarrier-mediated intracellular fluorescent agents (e.g., quantum dots or fluorescent protein) delivery for intracellular labeling and imaging.

molecules has the potential for genetic modification and regulation of plant metabolism. However, despite all the benefits, the principle of safety-by-design must be heeded to address community concerns (e.g., use of ENPs in consumer products) about the potential adverse effects of novel ENPs on ecological systems [4].

Here, we review the applications of phytonanotechnology, and discuss the uptake, translocation, activity, and risks associated with the use of ENPs in this field. Given that the physiochemical properties of ENPs are key in understanding their interactions with plants, we also briefly review advanced analytical techniques used for their detection, quantification, and characterization both *in vivo* and *in vitro*.

Glossary

Carbon nanotubes (CNTs): allotropes of carbon that have a cylindrical nanostructure with diameters ranging from <1 nm to 50 nm. They are categorized as either single-walled nanotubes (SWNTs) or multi-walled nanotubes (MWNTs).
Engineered NPs (ENPs): nanomaterials that are intentionally produced and designed with specific properties related to their shape, size, surface properties, and chemistry.
Magnetic NPs: NPs that contain magnetic materials of elements such as Fe, Ni, Co, and their chemical compounds. This type of NP can be manipulated for targeted delivery using magnetic field gradients.
Mesoporous silica NPs (MSNs): NPs that comprise a honeycomb-like porous structure with tunable pore size and tunable outer particle diameter in the nanometer range. This type of NP has hundreds of empty channels that are capable of encapsulating or absorbing large amounts of agrochemicals or bioactive molecules.
Nano quantitative structure-activity relation (nano-QSAR): a model used to predict biological responses based upon the physicochemical properties of NPs.
Nanofertilizers: fertilizers contained within nanostructured formulations that can be delivered to targeted sites to allow release of active ingredients. This release can be in response to environmental triggers or plant demands.
Nanoparticles (NPs): materials that have external dimensions or internal surface structures with two or three dimensions between 1 and 100 nm.
Nanotechnology: refers to the science, engineering, and technology of controlling, building, and restricting materials and devices at the nanoscale.
Phytonanotechnology: the application of nanotechnology in the plant sciences and plant production systems.
Quantum dots (QDs): tiny particles or nanocrystals of a semiconductor material with diameters ranging from 2 to 10 nm. This type of NP can produce a distinctive fluorescence that can be used for subcellular labeling and imaging.
Single particle inductively coupled plasma mass spectrometry (SP-ICP-MS): a type of time-resolved