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Agricultural Nanotechnologies: what are the current possibilities?

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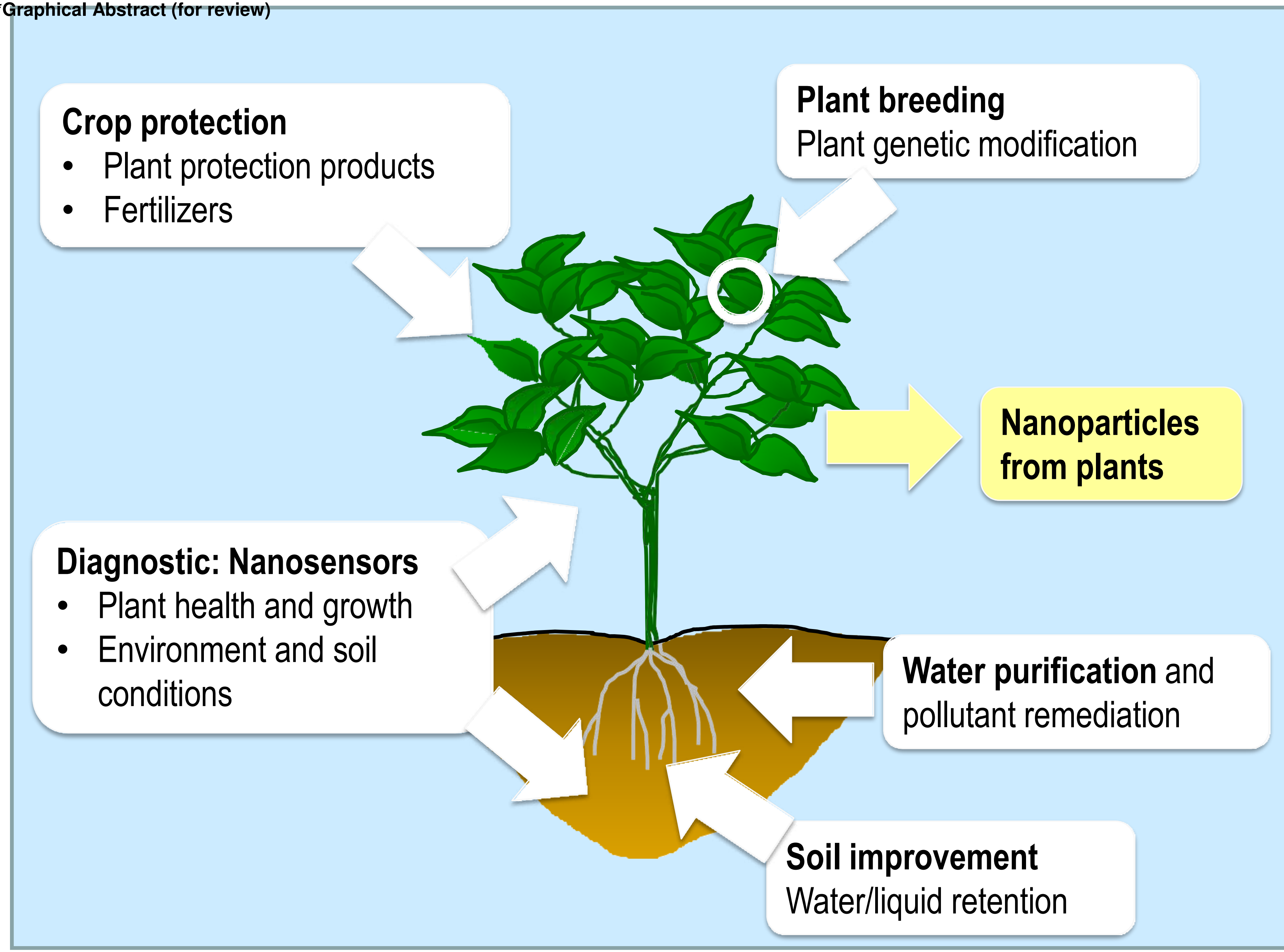
The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

*Graphical Abstract (for review)



Research highlights

- Nanotechnology is one of the six Key Enabling Technologies of the European Commission for sustainable competitiveness and industrial growth.
- Researchers are seeking in nanotechnology a new source of key improvements for the agricultural sector.
- Despite the potential advantages, applications in the agricultural sector have not yet made it to the market.
- Agricultural nanotechnologies did not demonstrate a sufficient economic return that could counterbalance the high initial investments.
- The way the regulation is designed is crucial, since it can affect products that are already on the market from decades.
- Public opinion towards nanotechnology is currently not negative and nanotech products with clear benefits could drive consumer acceptance.

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Agricultural Nanotechnologies: what are the current possibilities?

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Abstract

Nanotechnology is recognised by the European Commission as a Key Enabling Technology that contributes to sustainable competitiveness and growth in several industrial sectors. The current challenges of sustainability, food security and climate change are engaging researchers in exploring the field of nanotechnology as new source of key improvements for the agricultural sector. However, concrete contributions are still uncertain. Despite the numerous potential advantages of nanotechnology and the growing trends in publications and patents, agricultural applications have not yet made it to the market. Several factors would explain the scarcity of commercial applications. On the one hand, industry experts stress that agricultural nanotechnology did not demonstrate a sufficient economic return to counterbalance the high initial production investments. On the other hand, the new nanotech regulation in the EU requires further discussion and agreement among parties that might create regulatory uncertainty for products already on the market and thereby affect public perception. However, recent studies demonstrate that public opinion is not negative towards nanotechnology and that the introduction on the market of nanotech products with clear benefits will likely drive consumer acceptance of more sensitive applications. Additionally, the rapid progress of nanotechnology in other key industries may over time be transferred to agricultural applications as well, and facilitate their development.

Main text

Nanotechnology is recognised by the European Commission as one of the six Key Enabling Technologies that contribute to sustainable competitiveness and growth in several fields of industrial application [1]. The new chemical and/or physical properties of nano-scale particles provide useful functions [2] that are being rapidly exploited in medicine, biotechnology, electronics, material science and energy sectors, among others.

These promising developments concern also the agricultural sector, in which continuous innovation is strongly needed because of the arising global food security and climate change challenges. In the past, agriculture benefited from several and different technological innovations, like hybrid varieties, synthetic chemicals and biotechnology, and researchers are now seeking in nanotechnology a new source of key agricultural improvements. However, while the food industry is showing to be clearly benefited from nanotechnology (in particular for food processing, distribution, packaging and functional food), its real contribution to the agricultural sector is still uncertain.

According to leading R&D analyses[1], research on agricultural nanotechnology applications is ongoing for largely a decade by now, searching for solutions to several agricultural and environmental challenges, such as sustainability, improved varieties and increased productivity. Several authors show the growing trend of both scientific publications and patents in agricultural nanotechnology, especially for disease management and crop protection [3-5]. Nanomaterials in agriculture aims in particular to reduce the amount of

[1] The Institute for Prospective Technological Studies (IPTS) of the Joint Research Centre (JRC) of the European Commission (EC) organised a Workshop in November 2013 aiming to reveal the actual contribution of nanotechnology to the agricultural sector. The workshop focused on reviewing the state-of-the-art of R&D of agricultural nanotechnology, discussing current and potential markets of nano-products with applications in crop production and reviewing the regulations concerned by agricultural nanotechnologies applications. Leading scientists, experts, regulators and representatives of the farming and industrial sectors actively participated at the workshop, to present research and industry results and discuss experiences. Full proceedings of the workshop have been released electronically: JRC report, EUR 26625 EN – 2014. http://publications.jrc.ec.europa.eu/repository/handle/111111111/31846).

sprayed chemical products by smart delivery of active ingredients, minimize nutrient losses in fertilization [4] and increase yields through optimized water and nutrient management. Nanotechnology derived devices are also explored in the field of plant breeding and genetic transformation [6]. Additionally, agriculture can be a source of bio-nanocomposites with enhanced physical-mechanical properties that can be extracted from traditionally harvested materials, like wheat straw and soy hulls, for bio-industrial purposes [7]. Table 1 provides an overview of the most relevant agricultural nanotechnology applications.

Despite these potential advantages, nanotechnology applications in the agricultural sector are still comparably marginal and have not yet made it to the market to any larger extent in comparison with other industrial sectors. The wave of research discoveries seems to be mainly claimed by the academic world or small enterprises, while big industries reveal a large patent ownership. The trends of patent applications (mainly from agro-chemical companies) are continuously growing, but no new nano-based products for the agricultural sector have reached the market. This suggests that applicants are actively patenting and keeping broad patent claims in order to assure future freedom to operate and to guarantee future exploitation in case of promising commercial developments.

Large companies are investigating the potential that nanotech solutions offer in the agricultural field. However, according to industry experts, agricultural nanotechnologies so far did not demonstrate a sufficiently high economic interest. Nanotech products require high initial investments that can be counterbalanced only by large-scale field uses, which is currently not the case. Among the reasons of the difficulties of agricultural nanotechnologies developments at field level, industrial organizations address regulatory issues and public opinion.

One of the main aspects of regulating nano-materials is the achievement of a definition agreed among parties and, possibly, harmonized at international level. The definition of nano-materials seems not to be straightforward and is not just a matter of size as such. The nano-size can be applied to one or more dimensions and the form of the particles can be in aggregate, agglomerates or nanostructured materials. Moreover, since nanotechnology is applied in different industrial sectors, different regulatory bodies and pieces of regulations are involved for its safety assessment.

Many countries are now setting definitions and regulatory frameworks for nanotechnology [8]. In the EU, the main horizontal regulation covering nanotechnology applications is the REACH (EU Regulation on Registration, Evaluation, Authorisation and Restriction of Chemicals) [9], and there is an ongoing discussion on the definition, which covers nanoparticles in aggregates and agglomerates in the size range of 1-100 nm [10]. The current EC definition does not make the distinction between products that are intentionally manufactured to contain nano-scale materials, from those which contain particles that involuntary fall under the EC nano-definition and that are already in the market since decades. The proposed definition will be reviewed in the light of new experience and of scientific and technological developments.

Industry organisations have pointed to the effects that regulation, especially on labelling, can have on public opinion and the negative perception that this can create about a new technology. There is concern that consumers may reject products labelled as nano-products and this rejection might have also a retroactive effect, concerning products (i.e. nano-scale formulants such as clay, silica etc.) already present on the market for decades that involuntarily contain nano-size materials and that might fall under the nano-definition.

However, some studies on consumer preferences demonstrate that overall public opinion is not negative towards nanotechnology [11] and that it is particularly influenced by perceived benefits and usefulness of the technology. The results of the studies suggest that nanotech products with clear benefits and acceptable/low risks for the consumers, like medical and environmental applications, if introduced first into the market, could drive the acceptance of other applications to be introduced later on, e.g. pesticides solutions, which is an area where societal concerns already exists.

In conclusion, agro-nanotech innovative products are presenting difficulties in reaching the market, making agriculture still a marginal sector for nanotechnology. This is due in particular to the high production costs of large amounts of nanotech products, as required in the agricultural sector, unclear technical benefits on a large scale and legislative uncertainties, which can also influence public opinion. Nevertheless, the R&D landscape is very promising and is actively exploring the possibilities offered by nanotechnology in several agricultural applications. Additionally, nanotechnology is progressing at rapid pace in other fields. The knowledge gained in emerging key sectors, such as energy and packaging, may over time be transferred, or may provide spill-overs, to agricultural applications as well. For instance, improved fuel additives and lubricants can improve the performance and the carbon footprint of agricultural machineries and improved packaging measures can benefit farmers in reducing the degradation of the products before commercialisation. Also progress in environmental monitoring and drug delivery techniques [12] can positively affect the agricultural and livestock sector indirectly.

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Table

Table 1. Relevant applications in agricultural nanotechnology and examples of succesfull 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)	Anjali, C. H., Sharma, Y., Mukherjee, A. & Chandrasekaran, N. *Pest Management Science* **68**, 158-163 (2012)
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)	Milani, N. *et al.* *Journal of Agricultural and Food Chemistry* **60**, 3991-3998 (2012).
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)	http://www.geohumus.com/us/products.html
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)	McMurray, T. A., Dunlop, P. S. M. & Byrne, J. A. *J. Journal of Photochemistry and Photobiology A-Chemistry* **182**, 43-51 (2006).
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)	Vamvakaki, V. & Chaniotakis, N. A. *Biosensors & Bioelectronics* **22**, 2848-2853 (2007).
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)	Torney, F., Trewyn, B. G., Lin, V. S. Y. & Wang, K. *Nature Nanotechnology* **2**, 295-300 (2007).
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)	Alemdar, A. & Sain, M. *Bioresource Technology* **99**, 1664-1671 (2008).

Authors' biographies

Claudia Parisi is Research Fellow at the Joint Research Centre (JRC) of the European Commission, at the Institute for Prospective Technological Studies (IPTS) located in Seville-Spain. She is Biotechnologist and obtained her Ph.D. on New Plant Breeding Techniques at the University of Córdoba, Spain. Before joining the JRC, she followed internship programmes in FAO (Food and Agriculture Organization), in Rome, and EFSA (European Food Safety Authority), in Parma, Italy. She is currently dealing with research projects on emerging techniques in agriculture, including nanotechnology, and on the monitoring of the bio-based industry.

Mauro Vigani, is Research Fellow at the Joint Research Centre (JRC) of the European Commission, at the Institute for Prospective Technological Studies (IPTS) located in Seville-Spain. He got his Ph.D. in agricultural economics from the University of Milan, where he spent two years as post-doctorate at the Department of Economics, Management and Quantitative Methods. He has publications on international journals on topics such as the political economy of GMOs standards, GMOs patenting and agricultural labour market. He participated in European research framework projects and in several international conferences. His current research activity concerns the socio-economic impact of agricultural innovations (GM crops, nanotechnology, microalgae-based food and feed), farm productivity and risk management practices.

Emilio Rodríguez-Cerezo obtained a degree in Agronomy (1983) and a Ph.D. in Plant Pathology (1988) from Universidad Politécnica de Madrid (Spain). He started his career as researcher on biotech-based plant resistance to viral diseases and molecular epidemiology of disease outbreaks in crop plants. In 1997, he became active in the interface between biotechnology and regulation after being elected member of the first European Union's Scientific Committee for Plants (the embryo of what later became EFSA) in charge of risk assessment of GMOs. In 2001 he joined the European Commission's (EC) Joint Research Centre (JRC), the in-house scientific advisory body of the EC, at the Institute for Prospective Technological Studies (IPTS) located in Seville-Spain. Since then he has led a group of researchers providing policy support to policy makers in the fields of new biotechnologies in agriculture, coexistence between GM and non-GM agricultural production, and the social and economic impacts of biotech crops and the characterization of the EU bioeconomy.