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NEWS AND OPINIONS

Agricultural Nanotechnologies: What are the current possibilities?☆

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Abstract Nanotechnology is recognised by the European Commission as one of its six ''Key Enabling Technologies'' that contribute 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 could explain the scarcity of commercial applications. On the one hand, industry experts stress that agricultural nanotechnology does not demonstrate a sufficient economic return to counterbalance the high initial production investments. On the other hand, new nanotech regulation in the EU might create regulatory uncertainty for products already on the market and 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. The rapid progress of nanotechnology in other key industries may over time be transferred to agricultural applications as well, and facilitate their development.
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Nanotechnology is recognised by the European Commission as one of its 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 also concern the agricultural sector, in which continuous innovation is strongly needed because of increasing global food security and climate change challenges. In the past, agriculture benefited

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from many different technological innovations, including hybrid varieties, synthetic chemicals and biotechnology, and researchers are now seeking in nanotechnology a new source of agricultural improvements. However, while the food industry can be seen to be clearly benefiting 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 has been 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 have shown 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 sprayed chemical products by smart delivery of active ingredients, minimise nutrient losses in fertilisation [4] and increase yields through optimised water and nutrient management. Nanotechnology derived devices are also being explored in the field of plant breeding and genetic transformation [6]. Additionally, agriculture could be a source of bio-nanocomposites with enhanced physical—mechanical properties based on 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 large extent in comparison with other industrial sectors. The wave of research discoveries seems to be mainly claimed by the academic sector 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 do 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 not currently the case. Among the reasons for the difficulties of agricultural nanotechnology developments at field level, industrial organisations cite regulatory issues and public opinion.

One of the most important aspects of regulating nanomaterials is the achievement of a definition agreed among the involved 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. The nanoscale 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 regulations are involved in its safety assessment.

Many countries are now setting definitions and regulatory frameworks for nanotechnology [8]. In the EU, the main 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 such particles involuntarily and are already on the market. The proposed definition will be reviewed in the light of new experience and the latest scientific and technological developments.

Industry organisations have pointed to the effects that regulation, especially on labelling, can have on public opinion and the negative connotations it can create around 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) already present on the market that involuntarily contain nano-sized 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 introduced later on, e.g. pesticides solutions, where societal concerns already exist.

In conclusion, agro-nanotech innovative products are experiencing difficulties in reaching the market, making agriculture still a marginal sector for nanotechnology. This is due in particular to the high production costs of nanotech products, which are required in high volumes in the agricultural sector, unclear technical benefits and legislative uncertainties, as well as public opinion. Nevertheless, the R&D landscape is very promising and the possibilities offered by nanotechnology in several agricultural applications are being actively explored. Additionally, nanotechnology is progressing at rapid pace in other fields. The knowledge gained

[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.

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)	C.H. Anjali, Y. Sharma, A. Mukherjee, N. Chandrasekaran, Pest Manage. Sci. 68 (2012) 158—163
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)	N. Milani, et al., J. Agric. Food Chem. 60 (2012) 3991—3998
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)	T.A. McMurray, P.S.M. Dunlop, J.A. Byrne, J. Photochem. Photobiol. A-Chem. 182 (2006) 43—51
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)	V. Vamvakaki, N.A. Chaniotakis, Biosens. Bioelectronics 22 (2007) 2848—2853.
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)	[6]
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)	[7]

in other emerging 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 could also improve the performance and the carbon footprint of agricultural machinery and improved packaging measures could benefit farmers by reducing the degradation of products before consumption. Meanwhile progress in environmental monitoring and drug delivery techniques [12] could positively affect the agricultural and livestock sector indirectly.

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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 characterisation of the EU bioeconomy.