Chapter 7

Nanotechnology in Agriculture: New Opportunities and Perspectives

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Additional information is available at the end of the chapter

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Abstract

The prediction that in 2050 our planet will be populated by over 9 billion people is quite reliable. This will pose serious problems with food, water and energy supply, particularly in less-developed countries. Considering that the human pressure over natural resources has already reached critical levels, international agencies such as the World Bank and UN Food and Agriculture Organization (FAO) are soliciting scientific research in order to identify innovative solutions to support the primary sector. Nanotechnology is a rapidly evolving field with the potential to take forward the agriculture and food industry with new tools which promise to increase food production in a sustainable manner and to protect crops from pests. Such expectations are coupled with some uncertainties about the fate of nanomaterials in the agro-environment. However, the field application of engineered nanomaterials (ENMs) has not been properly investigated yet, and many aspects have only been considered theoretically or with models, which make it difficult to properly assess the usefulness of ENMs for plant fertilization and protection.

Keywords: agriculture, engineered nanomaterials, plant nanobionics, nanofertilizers, agricultural residues

1. Introduction

The current world population of 7.6 billion is expected to reach 8.6 billion in 2030, 9.8 billion in 2050 and 11.2 billion in 2100 [1]. This implies that new systems for food, water and energy will be needed to ensure food security. On the other hand, producing more food requires natural resources, land consumption, water supply and energy [2]. Thus, in the very near future, scientific research will be requested to provide new paradigms and practices to solve highly complex and diverse problems. Some examples are the following: (i) How will we feed our children? (ii) How can we simultaneously deliver increased crop yields and reduce the environmental impact of agriculture? (iii) How do plants contribute to the ecosystem services (e.g., photosynthesis, nitrogen fixation, and organic matter cycle) upon which humanity depends? Will world agricultural systems be able to cope with global climate change? [3].

Agriculture uses inefficiently the conventional inputs (land, water, energy, fertilizers and pesticides), and a large fraction of plant protection products applied per year are lost or are unavailable to the target [4, 5]. In addition, agriculture (cultivation of crops, livestock and deforestation) is a major contributor to greenhouse gas emissions producing about 24% of the total annual worldwide amount [6]. Waste production is another relevant issue of the primary sector. European countries produce approximately 90 million tons of agricultural wastes per year [7]. Nanotechnology has been recognized by the European Commission as one of its six "Key Enabling Technologies" that contributes to sustainable competitiveness and growth in several fields of industrial applications underpinning the shift to a greener economy [8]. Before beginning to deepen the analysis of the potential benefits of applying nanoscience to agriculture, we have to answer the following question: Why and how are nanotechnology and engineered nanomaterials (ENMs) expected to respond to the abovementioned issues?

Specific answers are provided by recent scientific literature which reports promising opportunities for nanoscience and nanotechnology to improve sustainability of agri-food systems [9]. From a quantitative perspective, by examining the growth of scientific literature on nanotechnology, it appears clearly that the interest on research in this field grew significantly between the end of twentieth century and the beginning of twenty-first century [10].

Compared to other fields of nanotechnology application, like medicine, materials and energy, agriculture is still a marginal sector. However, publications dedicated to agricultural applications tend to increase similar to those observed in other sectors. This is demonstrated by the increasing number of peer-reviewed scientific literature per year retrieved in Elsevier Scopus database. The query "Nanotechnology" and "Agriculture" was launched last October 10, 2017. The results were limited to the period 2000–2017 and filtered for scientific papers, reviews and conference papers. A number of 508 scientific products have been indexed in Scopus database: 264 (52%) papers, 143 (285%) reviews and 91 (18%) conference papers. As regards the distribution of publications among the most productive countries, United States and India share the research leadership in this field, having published together about 63% of papers (27 and 25%, respectively). China possesses the third rank (10%), whereas EU countries contribute with about 20% of publications.

The unique physicochemical properties of nanomaterials, that is, catalytic reactivity, high surface area, size and shape, have the potential to open new paradigms and to introduce new strategies in agriculture. Such new paradigms request also new terms. In a recently published book, the term "Agri-nanotechniques" was used. Since no specific definition for this word was provided, it has been used to indicate nanosystems utilized for the delivery of nutrient elements in crops [11]. In more general terms, the application of nanotechnology in the plant production systems or—more broadly—in plant science was defined with the term "Phytonanotechnology" [12]. However, since nanotechnology application in agriculture is in its infancy, it is very likely that new words will be invented in some time to indicate more specific technical developments.

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The state-of-the-art R&D of nanotechnology for the agricultural sector and their potential market in EU were firstly analyzed in 2013 during the workshop on "Nanotechnology for the agricultural sector: from research to the field" organized by the JRC-IPTS [13]. More recently, the European Food Safety Authority (EFSA) provides an inventory of current and potential future applications of nanotechnology in the agri-food sector and to review the regulation of nanomaterials in the EU as well as in non-EU countries [14].

So far, we have discussed in general about food security and the agricultural sector. In the next paragraphs, we will narrow down the analysis of nanotechnology applications specifically dedicated to field crop and plant production. Other sectors such as plant protection, animal husbandry and food technology will be not considered.

Specific agronomic applications of nanotechnology include (i) enabled delivery systems of release of agrochemicals allowing a controlled release of fertilizers, pesticides and herbicides, (ii) field-sensing systems to monitor the environmental stresses and crop conditions and (iii) improvement of plant traits against environmental stress and diseases [15, 16].

2. New opportunities

There are at least two fundamental aspects in the management of primary production on which research can produce significant advances to meet future needs: (i) increased production rate and crop yield, (ii) increased efficiency of resource utilization and (iii) reduction of waste production.

2.1. Increase production rate and crop yield

Crop yield increases have been achieved by utilizing plant breeding, fertilizers and plant-protection-products [17]. Since Green Revolution, which occurred during the decade 1960–1970, agricultural productivity growth has been in decline and at present we need a second revolution in agricultural technology [18]. However, rather than an increase in the doses of traditional agronomic factors, it is realistic that significant improvements in crop yield will come from improving the efficiency of the photosynthetic process.

Food security is based on plant photosynthesis. About 85% of plant species are C3 plants which are the most common and efficient in photosynthesis in cool wet climates. They include the cereal grains: wheat, rice, barley, oats, cotton, sugar beets, tobacco and soybean. In addition, most trees and most lawn grasses such as rye and fescue are C3 plants.

Photosynthetic organisms are able to convert radiant energy from solar light into chemical energy which is stored in sugars. The process coupled biophysical processes—absorption of photosynthetically active radiation (PAR) and electron transport—and biochemical processes —NADPH and ATP. Some targets have been identified to improve the photosynthesis [19].

Among these, the most serious candidate is the photosynthetic enzyme ribulose-1,5-bisphosphate carboxylase/oxygenase—in short, Rubisco. This molecule catalyzes the addition of CO_2 to the five-carbon compound ribulose bisphosphate, in the initial phase of the Calvin-Benson cycle [20]. Rubisco also reacts with oxygen in photorespiration. This is considered a wasteful process; in fact, it was verified that in C3 plants (25°C, current atmospheric [CO_2]), about 30% of fixed C is lost to recover Rubisco. For that reason, Rubisco is considered the physiological "bottleneck" of photosynthesis [21].

Let us take a step back and reconsider the biophysical processes of photosynthesis. More precisely, we take into consideration the energy source that promotes the process, that is, solar radiation. Visible light corresponds to 43% of solar light; it lies between 400 and 700 nm in the solar spectrum and approximately coincides with PAR. When sunlight reaches the leaf surface the photosynthetic pigments chlorophyll-a and chlorophyll-b absorb photons as allowed by their absorption spectrum and provide the energy to the biochemical pathway of photosynthesis [22]. The process is highly inefficient, the solar energy conversion efficiency (ratio of the energy stored to the energy of light absorbed) being 2.4 and 3.7%, respectively, for C3 and C4 healthy crops [23].

2.1.1. Plant nanobionics and photosynthesis

For years, important discussions and studies are under way to fill the knowledge gaps in order to overcome the limitation of photosynthesis. Significant efforts are made working on different strategies, including (i) engineering C3 crops to use C4 photosynthesis pathway [24], (ii) improving the efficiency of Rubisco [25], (iii) modifying the chlorophyll antenna size of chloroplast photosystems [26], (iv) improving the recovery rate from photoinhibition [27] and broadening the photosynthetic light waveband [28]. According to Evans, "recent technological developments now provide us with the means to engineer changes to photosynthesis that would not have been possible previously" [28].

There is no doubt whatsoever that nanotechnology is among these new tools. The scientific literature devoted to the relationships between plants and nanomaterials is not very large yet. However, a relatively large body of papers reported the positive effects of nanomaterials on photosynthesis. Early studies considered titanium oxide nanoparticles ($n\mathrm{TiO_2}$). And that is because the high photocatalytic activity of anatase crystal $n\mathrm{TiO_2}$ was hypothesized to have a role in the improvement of light absorbance by plant leaves, thus sustaining an increase in photosynthesis. In particular, it was demonstrated that $n\mathrm{TiO_2}$ protects the chloroplast from aging due to photochemical stress [29–30], activates Rubisco carboxylation promoting an enhancement of the photosynthetic rate [31–33] and positively influences biophysics traits of photosynthesis, such as electron chain transport and Chl-photophosphorylation activity [34]. Finally, in addition to photosynthesis, $n\mathrm{TiO_2}$ improves leaf water conductance and transpiration rate [35].

More recently, the original idea to merge nanomaterials with living plants to enhance their native functions and to give them non-native functions has been more accurately focused. This approach assumed the name of "plant nanobionics" [36] and potentially allowed to engineer faster-growing plants and become the key factor to design and develop artificial photosynthetic systems, a potential source of clean energy [37, 38]. In addition, it could also lead to other innovations that we cannot imagine at this time.

The first report demonstrating an application of plant nanobionics was provided by a research group from MIT. A suspension of single-walled carbon nanotubes (SWCNTs) was supplied by perfusion to leaves of *Arabidopsis thaliana* and to isolated chloroplasts of *Spinacia oleracea*. In both cases the SWCNTs were observed within the thylakoids and no symptoms of stress were recorded. The treatment increased the electron transport rate compared to control and the shelf life of isolated chloroplasts was extended by about 2 h. The authors proposed that the semi-conductor SWCNTs have a high electrical conductance and are able to capture solar energy in wavelengths that are weakly absorbed by chloroplasts. In particular, an enhancement in the light absorption profile of chloroplasts by increasing the light energy capture in UV and N-IR ranges of the spectrum was supposed [36].

In their experimental conditions the authors observed that SWCNT-chloroplast assemblies promoted over three times a higher photosynthetic activity than control and enhanced electron transport rate. On the one hand, there is no doubt that still extensive research would be needed to see the effects of plant nanobionics in terms of increased production of sugars as well as crop yield. On the other hand, the enhancement of a basic plant function in response to incorporation of nanomaterials was demonstrated as proof of concept [36].

2.2. Increase in efficiency of resource utilization

2.2.1. Principles of plant nutrition and fertilization

Optimal crop nutrition is a fundamental requirement for food security, which means that fertilization has a prominent role in modern agriculture. Crop yield is highly dependent on macronutrients (N, P, K, S, Ca, Mg) and micronutrients (B, Fe, Mn, Cu, Zn, Mo, and Cl) input to agricultural lands [39]. A conservative estimate obtained by examining the results of a number of long-term field studies on crop production suggested that from 30 to 50% of crop yield is attributable to commercial fertilizer nutrient inputs [40].

Nutrient use efficiency (NUE) is a measure of how well plants use the available mineral nutrients. In all agroecosystems NUE of crop plants is lower than 50% due to physical and chemical soil properties, leaching, gaseous losses and fertilizer characteristics [41], this is, for instance, in the case of urea [CO(NH2)2] which is one of the most important N-fertilizers (46% N by weight). Plants are not able to take up this molecule but the byproducts produced in soil after urea decomposition due to hydrolysis, volatilization and urease soil enzyme [42]. If ammonia is not readily assimilated by plant roots, then, large amounts of nitrogen are lost.

Since the fertilizer use between 1950 and 2000 increased about 20-fold and 7-fold for N and P, respectively [43], we have a 2-fold consequence. On one side, the lower efficiency of fertilizer dose implies that to maintain high production the production costs are increasing. From one another we have risks of environmental pollution.

As for micronutrients, though they are present in plants in concentrations generally below 100 ppm, they play fundamental physiological roles in plant metabolism, being activators of specific enzymes. Many micronutrients stimulate or are part of plant defensive systems against diseases or abiotic stress [44]. Moreover, plants are the sources of these essential elements for animals and humans [45]. Soil micronutrient deficiencies or insufficient micronutrient availability in soils limit crop productivity and nutritional value of food.

The most common method of micronutrient application for crops is soil application. Under unfavorable conditions (neutral to alkaline soil pH) microelements frequently precipitate and become less bioavailable [46]. It has been reported that the fertilizer-micronutrient use efficiency by crops is lower than 5% [47].

To overcome the soil limiting factors, a second strategy widely used to provide micronutrients to crops is via leaf treatments. However, plants primarily absorb nutrients through their roots. The amount of micronutrients that can be absorbed by leaves is limited, and they are not transported to the roots via the phloem (basipetal flux) [48].

2.2.2. Smart fertilizers for crop nutrition

Best management practices for fertilization are those that support the achievement of the main objectives of sustainable agriculture: productivity, profitability and environmental health. The improvement of NUE in crop production is one of the main pillars of this vision [52–54]. Nanotechnology can play an important role in the strengthening of agriculture sustainability, having provided the feasibility of the so-called "smart fertilizer." In other words, nanostructures act as carriers of nutrients and allowed their controlled release.

The design of smart fertilizers strongly influences the nutrient release and the minimization of losses. In field conditions such products are provided to crops via irrigation or sprayed to plant canopies. Through the application of nanotechnologies in agriculture the fertilization will be carried out in different ways. In particular, the nutrient elements will be possibly administered as follows:

i. Delivered as particles or emulsions of nanoscale dimensions: a research body is being developed which aims to clarify whether nanoparticles (e.g., fullerenes, carbon nanotubes, $n\mathrm{TiO_2}$, and $n\mathrm{SiO_2}$) in different growth stages of crops may or may not partially replace traditional fertilizer practices [55, 56].

ii. Encapsulated inside nanostructures designed to allow the controlled release of nutrients (**Figure 1**): to do so the outer shell of nanocapsules is engineered and programmed to open when stimulated by environmental factors or man-induced pulses. Here are some examples of possible control mechanisms [57]:

- Slow release: The capsule releases its payload slowly over a longer period of time so as to synchronize plant assimilation and limit leaching.
- Quick-release: The capsule shell breaks upon contact with a leaf surface.
- Specific release: The nutrient release occurs through a recognition mechanism between a receptor (molecule or functional group) bound to the shell and a target molecule.
- Moisture release: The shell breaks down and releases nutrients in the presence of water.

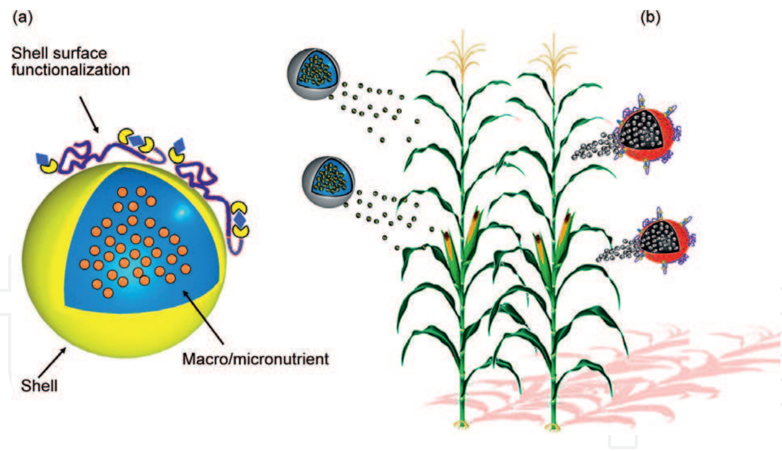

Figure 1. (a) Model of nanocapsule containing macro/microelements. Examples of opening strategies of nanocapsule: (b) release of nutrients as function of time to avoid or limit nutrient losses or designed to occur when a molecular receptor binds to a specific chemical.

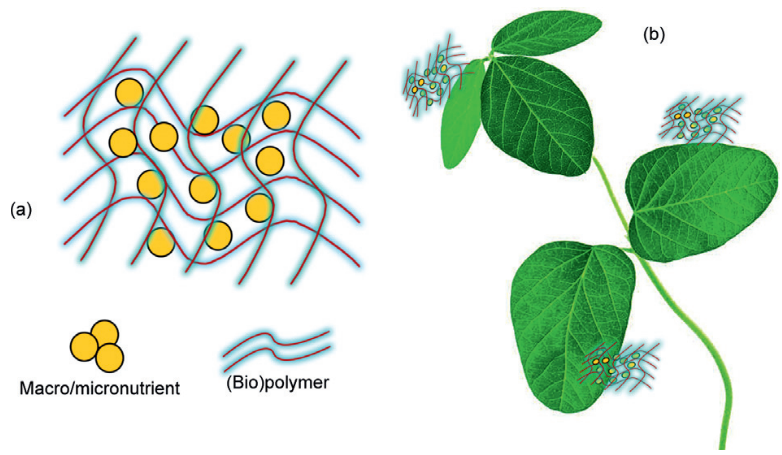

Figure 2. (a) Model of biopolymeric structure containing macro/microelements. (b) Deposition onto the crop leaf after spray treatment.

- pH release: The shell breaks up only in specific alkaline/acidic environment (e.g., within plant tissues or inside a cell).
- Magnetic/ultrasonic pulses: The shell opens in response to a magnetic or ultrasonic pulse emitted by a man-controlled system (precision agriculture).

iii. Delivered in a complex formed by nanocapsules incorporated in a matrix of organic polymers of biological or chemical origin which act as a carrier (**Figure 2**): Both of them provide the expected traits to nanofertilizers. However, natural substances should be preferred as they are easy available, biodegradable and cheaper than the synthetic ones [58]. The properties of the new nanostructure allow a controlled release of nutrients as a function of time or after interactions with the environment. Studies are currently being conducted to test the potential of different materials, such as zeolites [59–61], polyacrylic acid [62] and chitosan [63].

As far as the effectiveness of nanofertilizers is concerned, it must be said that the potential of nanofertilizer application has not been extensively studied yet. However, some successful examples demonstrated that such new formulates significantly improve the efficiency of fertilization [64–70].

The challenge for research is to develop and test carriers that allow the controlled release of nitrogen, following a schedule possibly synchronized with the physiological needs of crops. We are still at a stage where studies on interactions between nanomaterials and biota provide conflicting results. This occurs also for studies on nanofertilizers.

2.2.3. Large-scale use of nanofertilizers

There is no question that nanotechnology is a revolutionary science. However, in several fields of application there are good and bad components to deal with. Referring to nanofertilizers it should be emphasized there are still some uncertainties.

Despite great expectations, both large-scale industrial production of nanofertilizers and their utilization are yet to be realized. This is certainly due to the lack of clear legislative indications. For example, in the European Union, the work to prepare a legislative and regulatory framework is actively under way.

Another controversial point is that, when we look at the recent literature, surprisingly, it can be easily verified that research has neglected macronutrients to focus more in the direction of micronutrients [49–51, 71–73]. This is noteworthy; in fact, although microelements are very important in plant metabolism, crop yield is mainly influenced by N, P and K nutrition.

In conclusion, there are still great expectations that need to be satisfied. In accordance with international and national agencies dealing with sustainable agricultural development and food security (FAO, UNEAP, USEPA, EEA), applied research on nanotechnology in agriculture should be re-oriented according to precise priorities. The development of N and P nanofertilizers is certainly one of such priorities.

2.3. Internet of NanoThings in agriculture

The first definition of precision agriculture (PA) was “an integrated information- and production-based farming system that is designed to increase long term, site-specific and whole farm production efficiency, productivity and profitability while minimizing unintended impacts on wildlife and the environment.” It was provided in 1997 by the US House of Representatives [74]. Subsequently the definition narrowed and implemented with the concept of site-specific crop management (SSCM), which is “… a form of PA whereby decisions on resource application and agronomic practices are improved to better match soil and crop requirements as they vary in the field” [75]. This new vision implies that PA is a constantly evolving management strategy, ready to implement—where available—new technologies.

Applications that derive from convergence between Internet of Things (IoT) and nanotechnologies are developing very rapidly in industrial, information and communication technologies, and biomedical sectors. In addition, the future interactions between the Internet and nanodevices

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introduce a new perspective which has been referred to as the "Internet of NanoThings" (IoNT) [76, 77]. Needless to say, nanotechnology is the new frontier of PA.

2.3.1. Nanobiosensors

Nanobiosensors (NBSs) are analytical devices having at least one dimension no greater than 100 nm. Structured as nanoparticles, nanotubes, nanowires or nanocrystals, NBSs are manufactured for monitoring plant fractions, soil and water in the agroecosystem. By exploiting the physico-chemical properties of nanomaterials, NBSs represent a powerful tool with advanced and improved features compared to existing analytical sensors and biosensors that combine biological element recognition with chemical or physical principles [78]. Biological information is converted by a transducer into a signal yielded by an electronic component. This capability allows the agronomist with an accurate and real-time control of the needs of crops in terms of water and nutrient supply and early symptoms of diseases [79].

A properly designed network of nanosensors would allow the optimization of crop yield and the most efficient agronomic management of factors, such as fertilizers, water, herbicides and pesticides.

Typically, an NBS consists of three components [80, 81]:

i. Biological sensitive probe: a sensing element which interacts with the target (biomolecule) producing a signal proportional to the biomolecule concentration. Some examples of probe/biomolecule interaction are: (*i*) antibody–antigen, (*ii*) nucleic acid interactions (*iii*) enzymatic interactions and (*iv*) cellular interactions (i.e., microorganisms, proteins).

ii. Transducer: a physical component responsible for converting the recognition signal events into a digital signal. The nanomaterial properties suggest managing different kinds of signals such as electrochemical, optical and mass-sensitive signals.

iii. Data recording unit: it consists of an amplifier and signal processor that are responsible for data transferred and storage.

For plant monitoring applications, we therefore deploy a monitoring system comprising a hierarchical arrangement of nano- and microscale network devices (**Figure 3**). The control units manage clusters of nanodevices and the data flow. Data should be directed to gateways which relay the collected data from the nanonetwork to the Internet [82].

Large numbers of nanoscale-sensing devices could be positioned on the plant leaves through suspension in a spray treatment. At this time, this technology is at its very early stage. For its refinement, it will also be necessary to design spraying machines capable of adequately distributing suspensions with nanosensors onto crop canopies.

Nanonetworks for monitoring plant conditions can alert automatically suggesting a more efficient usage of crop inputs (e.g., fertilizers, water, pesticide, etc). Thus, the real time and monitoring of the crop growth lead to accurate and on-time decisions, reduced costs and waste, improved quality of production and above all sustainable agriculture.

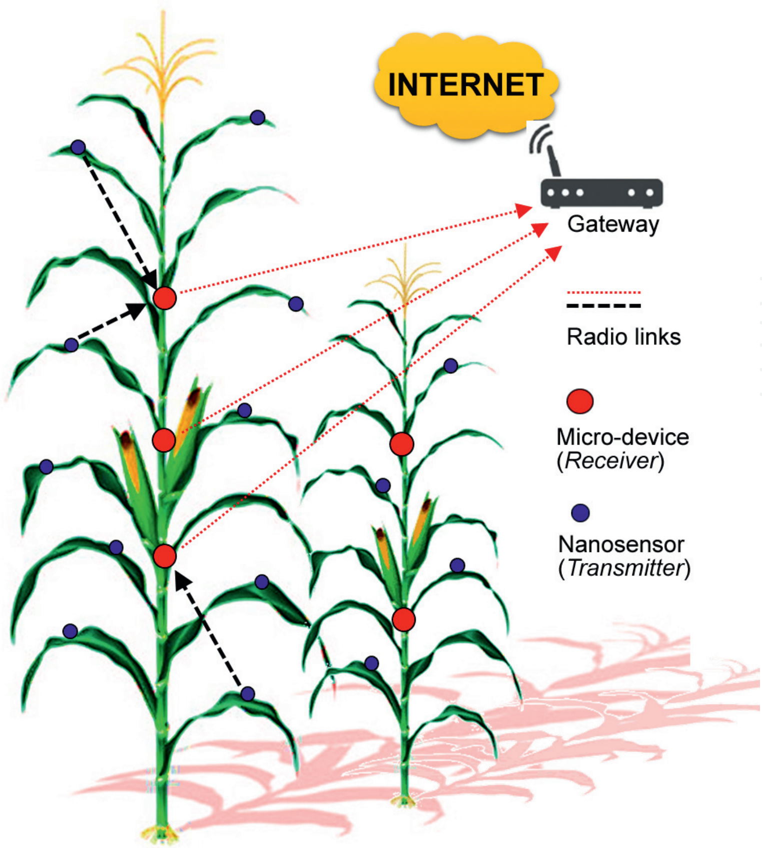

Figure 3. Structure and components of a nanonetwork designed for plant monitoring applications.

Finally, the use of nanobiosensors for high-resolution crop monitoring could be a very useful tool for plant science research. The real-time continuous measurement of plant metabolites and hormones will make a deeper understanding and control of plant biosynthetic pathways in ways not possible.

2.4. Valorization of agricultural residues for production of nanomaterials

There is a growing awareness of the importance of sustainability, in particular bearing in mind the increase of global population [1]. This issue is intimately linked to the implementation of a circular economy based on regeneration of resources. One of the pillars of circular economy is waste reduction.

Organization for Economic Cooperation and Development (OECD) defines agricultural waste as "waste produced as a result of various agricultural operations including manure and other wastes from farms, poultry houses and slaughterhouses; harvest waste; fertilizer run-off from fields; pesticides that enter into water, air or soils; and salt and silt drained from fields" [83].

A meaningful proportion of agri-food production is lost in the form of residues and wastes [84]. For this reason, it will be of the utmost importance to explore innovative technologies capable of providing new opportunities to achieve full sustainability. It is believed that nanotechnology can significantly contribute also in this direction [85]. The development of advanced methods for valorization and the exploitation of agricultural raw materials and wastes are relevant contributions of nanotechnology toward strengthening the basic principles of the circular economy. The following are suggested as illustrative examples of this concept.

2.4.1. Cellulose nanofibers

Cellulose is the most abundant biopolymer available on the Earth, being the main component of plant tissues. The primary occurrence of cellulose is the existing lignocellulosic material in wood which is the most important industrial source of cellulose. Other cellulose-containing materials include agriculture residues, water plants, grasses and other plant substances [86]. It is estimated that 10^{11}–10^{12} tons per year of cellulose are worldwide produced by photosynthesis [87].

In plant tissues micro and macrofibrils represent the construction units of the hierarchical structure of cellulose fibers (**Figure 4**). Microfibrils, in turn, consist of elementary fibrils (nanofibres) which have a diameter comprised in the range 3–35 nm depending on the cellulose source (**Figure 4**) [88].

In recent years, nanocellulose has been attracting much attention as a new bio-based nanomaterial with excellent optical properties, high strength and specific surface area [89, 90]. Nanocellulose can be extracted and chemically modified for a wide range of applications in the field of nanocomposites [91]. Various agricultural crops and residues, such as soy hulls and wheat straw, sugar beet pulp, potato pulp and rutabaga, are already considered as raw materials for new cost-effective methods of nanocellulose production [92–95].

2.4.2. Rice husk-derived Si nanomaterials

FAO's preliminary forecast of global paddy production in 2017 is set at 503.8 million tons (milled basis) [96]. About 25% of this production is rice husk (RH) which is disposed as a by-product of rice milling. The RH is the coating on a grain of rice which has the role to protect the seed during the crop cycle. RHs are mainly composed of lignocellulose (ca. 72–85 wt %) and silica (ca. 15–28 wt %) [97]. Silicon is the second element of importance in the Earth's crust. Grasses assimilate large amounts of Si during their entire life cycle and deposit it into phytoliths as amorphous hydrated silica (SO_2 nH_2O). The Si content in the ash of grasses can reach 50–70% [98].

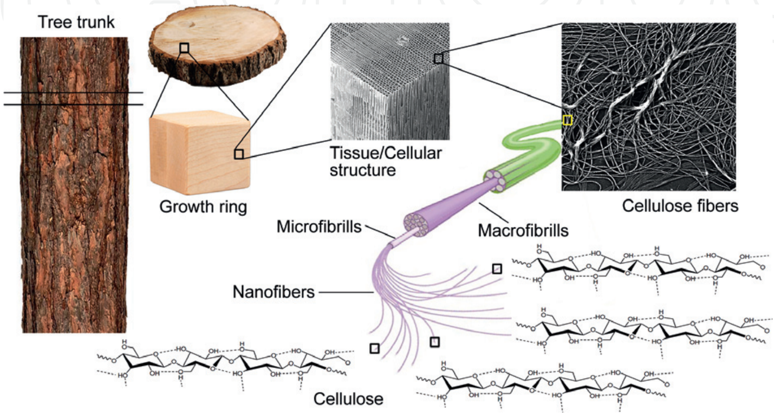

Figure 4. Hierarchical structure of cellulose fibers in wood biomass.

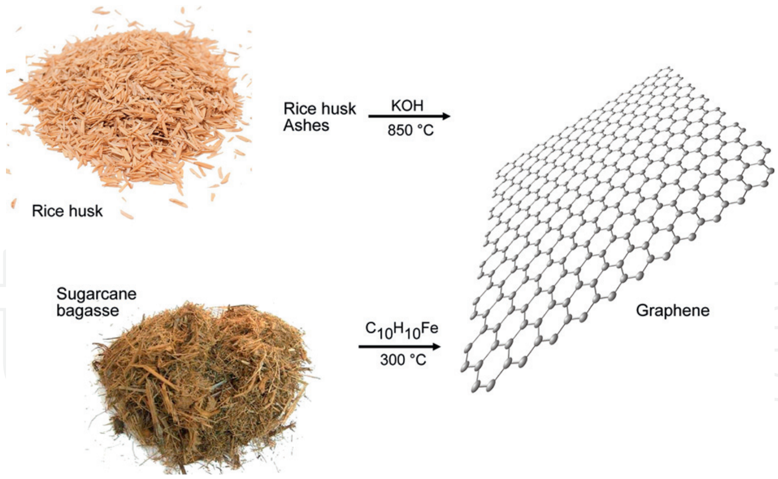

Figure 5. Production of graphene from agricultural wastes.

Silica nanoparticles (*n*Si) have numerous potential applications in drug delivery and biomedicine [99], and in agriculture, as well. According to the principles of green chemistry and among the available agricultural raw materials, RH is considered to be a cost-effective bioprecursor for biosynthesis of *n*Si.

2.4.3. Graphene

Graphene is a material consisting of a monoatomic layer of carbon atoms isolated in 2004 by Novoselov and Geim (University of Manchester, UK), who in 2010 received for that work the Nobel Prize in physics. Graphene has the mechanical strength of the diamond and the flexibility of the plastic and is already used in medicine, electronics, energy, defense and many other sectors. The European Commission, launched in 2013, financed The Graphene Flagship, a 10-year research initiative financed with € 1 billion, which involves more than 140 academic and commercial institutions in 23 countries.

Graphene is currently produced by mechanical and chemical exfoliation of graphite crystals, chemical synthesis and thermal chemical vapor deposition. Considering the large-scale production of graphene, the use of these methods poses several problems due to high process costs and the use of toxic substances. That is why, also in this case, there is considerable interest for the development of alternative, cheaper and environmental-friendly methods.

Recent studies demonstrated that it is possible to use rice husk and sugarcane bagasse to produce graphene in a rapid, scalable and cost-effective manner (**Figure 5**). It is very useful to test other raw agricultural materials to expand the possibility to exploit other wastes or crop byproducts.

3. Conclusions

In this chapter, we have examined some recently developed ideas concerning the possible contributions of nanotechnologies in the primary sector. At this moment, some ideas are, if

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not completely visionary, strongly projected into the future. Whereas some other hypotheses are very concrete, for some of them, the first experimental data are already available. Thus, in looking ahead to the future, we can be reasonably optimistic.

However, there are a number of concerns linked to the applicative aspects of the use of nanomaterials in agriculture which have to be addressed. How will nanofertilizers (or nanopesticides, nanoherbicides) be handled in field conditions? Which precautionary criteria should be considered? Which equipment or machines will be used? Will these be the same equipment or machines used for bulk materials? What should be the safety conditions for workers? On these aspects, and many others, the authorities will have to define rules. Obviously, on this point, there are great expectations from the industries.

In conclusion, the utilization of nanomaterials in agriculture still needs deep basic knowledge about the fate of nanomaterials in the agro-environment. However, a more mature and, at the same time, a very promising aspect of the interactions between agriculture and nanotechnology are that with regard to the valorization of waste materials. Therefore, it is appropriate to reiterate once again that nanotechnologies are in tumultuous evolution. This means that applications currently under development will soon be overtaken by other ideas that will solve other issues in the field of sustainable agriculture. This principle is nothing but the driving force of the development of knowledge and the strengthening of technology applications.

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Conflict of interest

The author declares no conflict of interest.

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