Embodiment of Nanobiotechnology in Agriculture: An Overview

Tareq A. Wani, Gulzar A. Rather, Mudasar Ahmad, and Zahoor A. Kaloo

1 Introduction

Nanotechnology being an emerging field has gained a marvelous role in agriculture sector and has brought radical changes in agricultural production. The development of new and novel nanotech-based equipment may help to augment efficiency and overcome challenges faced by the modern agricultural industry. A*griculture practice makes widespread use of industrially generated chemicals to rouse growth and inhibit pests, insects, and disease* (Yunlong and Smit 1994). Recently, nanotechnology has proved to have the potential to improve the agri-food sector, minimizing adverse human health problems, agricultural practices on environment and improving food productivity and security required by the predicted rise in global population, while promoting social and economic equity. In this backdrop, we select and report on recent trends in nano-material based systems and nano-devices that could benefit the food supply chain specifically on sustainable intensification and management of soil and wastes. Agriculture is always highly important and most stable sector to boost nation's economy as it provides raw materials for feed and food industries and companies. Limited natural resources such as water, land, soil, etc., and the growing population in the world has forced scientific community to develop green approaches for the sustainable agriculture development (Mukhopadhyay 2014). Agricultural nutrient balance is differed perceptibly with economic growth, and especially from this surmise, the development of the soil fertility is very much significant in developing countries (Campbell et al. 2014). The growth of agriculture is necessary for the eradication of poverty and hunger in order to get a hold on

T. A. Wani (✉) · M. Ahmad · Z. A. Kaloo
Department of Botany, University of Kashmir, Srinagar, India

G. A. Rather
Plant Biotechnology Division, CSIR-Indian Institute of Integrative Medicine, Jammu, India

K. R. Hakeem, T. B. Pirzadah (eds.), *Nanobiotechnology in Agriculture*,
Nanotechnology in the Life Sciences, https://doi.org/10.1007/978-3-030-39978-8_6

the present situation. Therefore, we should have to take one bold step for agriculture development. In present world, most of the population lies under below poverty levels, scattered across the rural areas where agriculture enlargement has not been so effective. Therefore, new technology should have to be adopted that decidedly focuses on getting better agricultural production (Yunlong and Smit 1994). The agriculture development also depends on the social inclusion, health, climate changes, energy, ecosystem processes, natural resources, good supremacy, etc., which must be documented in specific target oriented goals (Thornhill et al. 2016). No doubt that the sustainable growth of agriculture totally depends on the new and innovative techniques like nanotechnology. If we like to go in the year 1959 Feynman's lecture on "Plenty of room at the bottom," from this very day, the nano-process is in underway (Feynman 1996). Later on Professor Norio Tanaguchi proposed the actual term of nanotechnology (Bulovic et al. 2004; Gibney 2015). Subsequently, nanotechnology developed in more dramatic ways, as more recent appliances develop to isolate nanomaterials in more precise ways. Additionally, the number of publications related to the term of "nano" was also grown exponentially. About 14,000 documents with word nanotechnology in food or agriculture were listed until 2016 pointing towards the importance gained by this field. Also about 2707 patents matched this criteria are found in world patent database. The world market size of nanotechnology in 2002 was about US$ 110.6 billion and predicted to grow to US$ 891.1 billion in 2015 according to analysis of Helmut Kaiser Consultancy. In the present century, there is a big demand for fast, reliable, and low-cost systems for the detection, monitoring, and diagnosis for biological host molecules in agricultural sectors (Vidotti et al. 2011; Sagadevan and Periasamy 2014). The application of chemically synthesized nanomaterials nowadays is considered as toxic in the nature; however, biosynthesis of nanomaterials using microbial or phyto-engineering approach is safe and is considered as green nanotechnology (Prasad et al. 2014). Green nanotechnology is a safe process, energy efficient, reduces waste and reduces greenhouse gas emissions. Use of renewable materials in production of such products is beneficial, thus these processes have low influence on the environment (Prasad et al. 2014, 2016). Since the last decade, there is a paradigm shift toward the green synthesis of nano-particles and its implementation in agro-industry. Still it is not clear how the environmental sustainability of green nanotechnology will be achieved in future? These risks must be mitigated in advanced green nanotechnology solutions (Kandasamy and Prema 2015).

The development of the high-tech agricultural system with use of engineered smart nano-tools could be excellent strategy to make a revolution in agricultural practices, and thus reduce and/or eliminate the influence of modern agriculture on the environment as well as to enhance both the quality and quantity of yields (Sekhon 2014; Liu and Lal 2015). Further the development of biosensors in the smart agro-food sector is also a good field for exploitation of many strengths of nanotechnology (Sertova 2015; Fraceto et al. 2016). Additionally, use of nanomaterials let to miniaturize many biosensors to small and compact/smart devices such as nanosensors and other nano-systems that are very important in biochemical analysis (Viswanathan and Radecki 2008; Sertova 2015; Fraceto et al. 2016). Keeping in

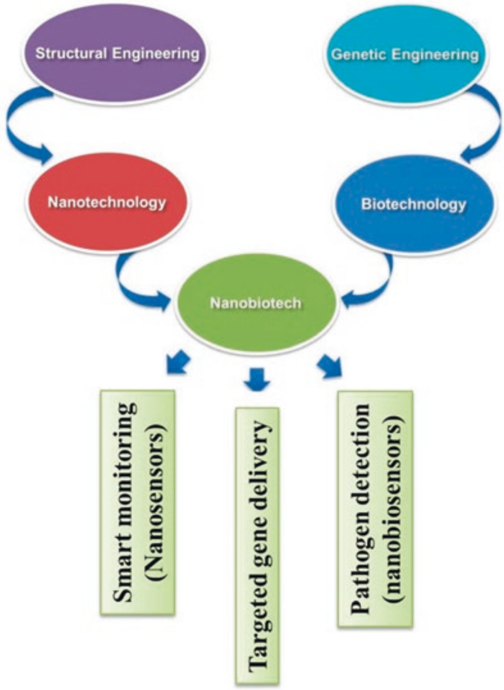

Fig. 1 Flowchart involving the convergence of nanotechnology and biotechnology results in nanobiotechnology, which entails knowledge of structural and genetic engineering

view of the above facts, here we summarize encapsulation of nanoparticles and how nanotechnology boosts the agriculture sector besides its negative impact on the environment (Fig. 1).

2 Micro- and Nano-encapsulation

Encapsulation is defined as the process in which the given object is surrounded by a coating or embedded in homogeneous or heterogeneous matrix, thus this process results in capsules with many useful properties (Rodríguez et al. 2016). The benefits of encapsulation methods are for protection of substances/objects from adverse environments, for controlled release, and for precision targeting (Ezhilarasi et al. 2012; Ozdemir and Kemerli 2016). Depending on size and shape of capsules different encapsulation technologies are mentioned, while the (macro) encapsulation/coating results in capsules in macro-scale, whereas the micro- and nano-encapsulation will give particles in micro- and nano-scale size (Ozdemir and Kemerli 2016). Nano-capsules are vesicular systems in which the substances are confined to a cavity consisting of an inner liquid core enclosed by a polymeric membrane (Couvreur et al. 1995). Recently, NPs are getting significant attention for delivery of drugs, for protection and increase in bioavailability of food components or nutraceuticals, for food fortification, and for the self-healing of several materials, and also it possesses big prospective phenomenon in plant science (Ozdemir and Kemerli 2016). Furthermore, the development of this technology will build more possibility to create new drugs with precise therapeutic action on embattled tissues. Nano-capsules can potentially be used as MRI-guided nanorobots or nanobots (Vartholomeos et al. 2011). Recently, a wide range of potential applications of nanotechnology have been envisaged also in agriculture, leading to intense research at both academic and industrial levels (Parisi et al. 2015). Indeed, the unique properties of materials at nano-scale make them suitable candidates for the design and development of novel tools in support of a sustainable agriculture. Some of the main applications of these nano-tools in agriculture are reported in the following paragraphs.

3 Precision Farming

The process of maximizing crop yields and minimizing the usage of pesticides, fertilizers, and herbicides through efficient monitoring procedures is referred to as precision farming. Precision farming utilizes remote sensing devices, computers, and global satellite positioning systems to analyze various environmental conditions in order to determine the growth of plants under these conditions and identify problems related to crops and their growing environments. Precision farming helps determine plant development, soil conditions, usage of water and chemicals, fertilizers and seeding and controls environmental pollution to a minimum extent by reducing agricultural waste (Prasad et al. 2017; Pirzadah et al. 2019). The implementation of nanotechnology in the form of small sensors and monitoring devices will create a positive impact on the future use of precision farming methodologies. Nanotech-enabled systems help in increasing the use of autonomous sensors that are linked into GPS systems to provide efficient monitoring services focused on crop growth and soil conditions. The usage of smart sensors in precision farming will result in increased agricultural productivity by providing farmers with accurate information that will enable them to make accurate decisions related to plant growth and soil suitability.

4 Nano Delivery Systems

There are many regulatory restrictions placed on pesticides in agriculture today. Pesticides such as DDT, which have caused extreme environmental hazards, have increased public and regulatory awareness of the use of chemicals in farming, shifting the industry's focus on to the use of integrated pest management systems, combining smarter and more targeted use of chemicals with granular monitoring of plant health. These agricultural systems can make excellent use of nanotech-enabled "smart" devices that can perform a dual role of being a preventive and early warning system (Singh et al. 2017). These devices can identify plant-related health issues even before they become visible to the farmers and simultaneously provide remedial measures. User-friendly and eco-friendly nano delivery systems for nutrients and pesticides have started to find their place in the market. These can allow the use of pesticides with the absolute minimum risk of environmental damage. Companies have implemented nano-emulsions in commercial pesticide products. Syngenta, a leading agrochemical corporation, produces a quick-release microencapsulated product, which is available under the name Karate® ZEON (Misra et al. 2016).

5 Systems for Sustainable Intensification in Agriculture

Sustainable intensification is a concept related to a production system aiming to increase the yield without adverse environmental impact while cultivating the same agricultural area (The Royal Society 2009). This paradigm provides a framework to evaluate the selection of the best combination of approaches to agricultural production considering the influence of the current biophysical, social, cultural, and economic situation (Garnett and Godfray 2012). In this context, novel nanomaterials based on the use of inorganic, polymeric, and lipid nanoparticles synthesized by exploiting different techniques (e.g., emulsification, ionic gelation, polymerization, oxidoreduction, etc.) have been developed to increase productivity. They can find application, as an example, for the development of intelligent nano-systems for the immobilization of nutrients and their release in soil. Such systems have the advantage to minimize leaching, while improving the uptake of nutrients by plants, and to mitigate eutrophication by reducing the transfer of nitrogen to groundwater (Liu and Lal 2015). Furthermore, it is noteworthy to mention that nanomaterials could also be exploited to improve structure and function of pesticides by increasing solubility, enhancing resistance against hydrolysis and photodecomposition, and/or by providing a more specific- and controlled-release toward target organisms (Mishra and Singh 2015; Grillo et al. 2016; Nuruzzaman et al. 2016).

6 Soil Quality Improvement Through Nanotechnology

Hydrogels, nanoclays, and nanozeolites have been reported to enhance the water-holding capacity of soil (Sekhon 2014), hence acting as a slow-release source of water, reducing the hydric shortage periods during crop season. Applications of such systems are favorable for both agricultural purposes and reforestation of degraded areas. For example; organic polymer and carbon nanotubes and inorganics like nano-metals and metal oxides nanomaterials have also been used to absorb environmental contaminants (Khin et al. 2012), increasing soil remediation capacity and reducing times and costs of the treatments.

7 Nanomaterials as Agents to Stimulate Plant Growth

Carbon nanotubes and nanoparticles of Au, SiO_2, ZnO, and TiO_2 can contribute to ameliorate development of plants by enhancing elemental uptake and use of nutrients (Khota et al. 2012). However, the real impact of nanomaterials on plants depends on their composition, concentration, size, surface charge, and physiochemical properties, besides the susceptibility of the plant species (Lambreva et al. 2015). The development of new protocols and the use of different analytical techniques (such as microscopy, magnetic resonance imaging, and fluorescence spectroscopy) could considerably contribute to understand the interactions between plants and nanomaterials.

8 Management of the Food Supply Chain Using Nano-tech Approach

Nanotechnology can find applications also in the development of analytical devices dedicated to the control of quality, bio/security, and safety not only in agriculture, but also along the food supply chain (Valdes et al. 2009). In this context, nanosensors represent a powerful tool with advanced and improved features, compared to existing analytical sensors and biosensors. Nanosensors are defined as analytical devices having at least one sensing dimension no greater than 100 nm, fabricated for monitoring physico-chemical properties in places otherwise difficult to reach. They have unique surface chemistry, distinct thermal, electrical, and optical properties, useful to enhance sensitivities, reduce response times, and improve detection limits, and can be used in multiplexed systems (Yao et al. 2014). Considering the huge amount of research in this area, real applications of nanosensors for field analysis are unexpectedly scarce, implying the potential for a new market. In this perspective, nanotechnologies could enhance biosensor performance to allow real applications in agri-food industry. Indeed, thanks to important progresses in nanofabrication, laboratory analytical techniques, such as surface plasmon resonance, mass spectrometry, chromatography, or electrophoresis chips, can support the development of viable sensor components. However, the real need of the market is the realization of automated embedded systems which integrate bio-sensing components with micro/nanofluidics, data management hardware, and remote control by wireless networks. This is a key issue for nanotechnology, which can provide the decisive approaches as well as novel nanomaterials for the realization of bio-sensing devices (Scognamiglio 2013). Indeed, as described by Mousavi and Rezaei (2011) “Nanosensors help farmers in maintaining farm with precise control and report timely needs of plants.” Thus, it will be mandatory to address research efforts to the development of nanosensors to aid decision-making in crop monitoring, accurate analysis of nutrients and pesticides in soil, or for maximizing the efficiency of water use for a smart agriculture. In this context, nanosensors could demonstrate their potential in managing all the phases of the food supply chain, from crop cultivation and harvesting to food processing, transportation, packaging, and distribution (Scognamiglio et al. 2014). Among them, nanosensors for dynamic measurement of soil parameters (pH and nutrients, residual pesticides in crop and soil, and soil humidity), detection of pathogens, and prediction of nitrogen uptake are only few examples to foster a sustainable farming (Bellingham 2011). Controlled-release mechanisms via nano-scale carriers monitored by nanosensors integrated in platforms employing wireless signals will avoid overdose of agricultural chemicals and minimize inputs of fertilizers and pesticides during the course of cultivations, improving productivity and reducing waste. Networks of nanosensors located throughout cultivated fields will assure a real time and comprehensive monitoring of the crop growth, furnishing effective high-quality data for best management practices (El Beyrouthya and El Azzi 2014).

Nanotechnologists are hoping that this technology will transform the entire food industry by bringing about changes in the production, processing, packaging, transportation, and consumption of food. Usage of nanotechnology in these processes ensures safety of food products, thus creates a healthy food culture and enhances the nutritional quality of foods. Smart food packaging systems can be developed using nanotechnology that in turn increases the shelf life of food products by developing active antifungal and antimicrobial surfaces, improving heat-resistance and mechanical properties, modifying the permeation behavior of foils, and detecting and signaling biochemical and microbiological changes. A number of companies have started to develop Smart Packaging systems—one such company is Bayer Polymers, who developed the Durethan KU2-2601 packaging film whose key purpose is to prevent drying of food content and protect the food content from oxygen and moisture. This packaging film is made from a number of silicate nanoparticles. Nanocapsules are added into food products in order to deliver nutrients, and nanoparticles when added to food increase the absorption of nutrients. An increasing number of companies are researching on additives that can be easily absorbed by the body and increase product shelf life. Bio-delivery Sciences International developed coiled nanoparticles called nano-cochleates that deliver nutrients and omega fatty acids to cells without causing any changes to the taste and color of food (Ravichandran 2010). The automation of irrigation systems is also a crucial requirement of smart agriculture, mainly in a scenario of water shortage. In this regard, sensor technology has the potential to maximize the efficiency of water use. Nanosensors estimating soil water tension in real time may be coupled with autonomous irrigation controllers. This feature allows a sustainable irrigation management based on drying soil, otherwise an approach too difficult for farmers because it involves evaluation of climate and crop growth aspects of high complexity (de Medeiros et al. 2001). Furthermore, nanosensors find also application in fast, sensitive, and cost-effective detection of different targets to ensure food quality, safety, freshness, authenticity, and traceability along the entire food supply chain. Surely, nanosensors represent one of the emerging technologies challenging the assessment of food quality and safety, being able to provide smart monitoring of food components (e.g., sugars, amino acid, alcohol, vitamins, and minerals) and contaminants (e.g., pesticides, heavy metals, toxins, and food additives). Food quality and food safety control represents a crucial effort not only to obtain a healthy food, but also to avoid huge waste of food products. The potential of nanosensor can also be demonstrated by the last trends on intelligent or smart packaging to monitor the freshness properties of food and check the integrity of the packages during transport, storage, and display in markets (Vanderroost et al. 2014). Many intelligent packaging involve nanosensors as monitoring systems to measure physical parameters (humidity, pH, temperature, light exposure), to reveal gas mixtures (e.g., oxygen and carbon dioxide), to detect pathogens and toxins, or to control freshness (e.g., ethanol, lactic acid, acetic acid) and decomposition (e.g., putrescine, cadaverine).

9 Nanotechnology and Agricultural Sustainable Development

The nanotechnology plays an important role in the productivity through control of nutrients (Mukhopadhyay 2014) as well as it can also participate in the monitoring of water quality and pesticides for sustainable development of agriculture (Prasad et al. 2014). Properties of NPs that include chemical composition, shape, surface structure, surface charge, behavior, extent of particle aggregation (clumping) or disaggregation, etc. have the influence on toxicity (Ion et al. 2010). For this reason even nanomaterials of the same chemical composition that have different sizes or shapes can exhibit their different toxicity. The implication of the nanotechnology research in the agricultural sector is becoming a necessary key factor for the sustainable developments as it leads to the production of nanofertilizers and nano-pesticides that helps to enhance production yield (Tables 1 and 2). In the agri-food areas pertinent applications of nanotubes, fullerenes, biosensors, controlled delivery systems, nano-filtration, etc. were observed (Ion et al. 2010; Sabir et al. 2014). This technology was proved to be as good in resources management of agricultural field, drug delivery mechanisms in plants, and helps to maintain the soil fertility. Moreover, it is being also evaluated steadily in the use of biomass and agricultural waste as well as in food processing and packaging system as well as risk assessment (Floros et al. 2010). Recently, nanosensors are widely applied in the precision agriculture for environmental monitoring of contamination in the soils and in the water (Ion et al. 2010). Nanomaterials not only directly catalyze degradation of waste and toxic materials but it also aids to improve the efficiency of microorganisms in degradation of waste and toxic materials. It is an interesting phenomena in considering the nano–nano interaction to remove the toxic component of the agricultural soil and make it sustainable (Ion et al. 2010; Dixit et al. 2015). The recent development of a nano-encapsulated pesticide formulation has slow-releasing properties with enhanced solubility, specificity, permeability, and stability (Bhattacharyya et al. 2016). These assets are mainly achieved through either protecting the encapsulated active ingredients from premature degradation or increasing their pest control efficacy for a longer period. Formulation of nano-encapsulated pesticides led to reduce

Table 1 List of some commercially available nanofertilizers

Commercial product	Content	Company
Nano-Gro™	Plant growth regulator and immunity enhancer	Agro Nanotechnology Corp., FL, United States
Nano Green	Extracts of corn, grain, soybeans, potatoes, coconut, and palm	Agro Nanotechnology Corp., FL, United States
Nano-Ag Answer®	Microorganism, sea kelp, and mineral electrolyte	Urth Agriculture, CA, United States
Biozar Nano-Fertilizer	Combination of organic materials, micronutrients, and macromolecules	Fanavar Nano-Pazhoohesh Markazi Company, Iran
Nano Max NPK Fertilizer	Multiple organic acids chelated with major nutrients, amino acids, organic carbon, organic micro nutrients/trace elements, vitamins, and probiotic	JU Agri Sciences Pvt. Ltd., Janakpuri, New Delhi, India
Master Nano Chitosan Organic Fertilizer	Water-soluble liquid chitosan, organic acid and salicylic acids, phenolic compounds	Pannaraj Intertrade, Thailand
TAG NANO (NPK, PhoS, Zinc, Cal, etc.) fertilizers	Proteino-lacto-gluconate chelated with micronutrients, vitamins, probiotics, seaweed extracts, humic acid	Tropical Agrosystem India (P) Ltd., India

the dosage of pesticides and human beings exposure to them which is environment-friendly for crop protection (Nuruzzaman et al. 2016), thus developing non-toxic and promising pesticide delivery systems for increasing global food production while reducing the negative environmental impacts to ecosystem (Bhattacharyya et al. 2016; Grillo et al. 2016).

10 Identification of Gaps and Obstacles

Despite considerable advances in identifying possible applications of nanotechnology in agriculture, many issues remain to be resolved in the near future before this technology may make significant contributions to the area of agriculture. Some of the main aspects that require further attention are: (1) development of specific hybrid carriers for delivering active agents including nutrients, pesticides, and fertilizers in order to maximize their efficiency following the principles of green chemistry and environmental sustainability (De Oliveira et al. 2014); (2) design of processes easily up-scalable at industrial level; (3) comparison of effects of nano-formulations/nano-systems with existing commercial products in order to demonstrate real practical advantages; (4) acquisition of knowledge and developments of methods for risk and life-cycle assessment of nanomaterials, nano-pesticides, nanofertilizers, as well as assessment of the impacts (e.g., phytotoxic effects) on non-target organisms such as plants, soil microbiota, and bees; (5) advances in the regulations about the use of nanomaterials (Amenta et al. 2015). In this context, the

Table 2 List of commercially available nano-pesticides/nanoherbicides

Carrier system	Agent	Purpose	Method
Chitosan	Imazapic and Imazapyr	Cytotoxicity assays	Encapsulation
Silica	Piracetam, pentoxifylline, and pyridoxine	Perfused brain tissue	Suspension
Alginate	Imidacloprid	Cytotoxicity, sucking pest (leafhoppers)	Emulsion
Polyacetic acid-polyethylene glycol-polyacetic acid	Imidacloprid	Decrease the lethal concentration	Encapsulation
Carboxymethyl chitosan	Methomyl	Control release for longer time period	Encapsulation
Chitosan/ tripolyphosphate	Paraquat	Lower cyto- and genotoxicity	Encapsulation
Chitosan/ tripolyphosphate chitosan-saponin chitosan-Cu	Chitosan, saponin, $CuSO_4$	Antifungal activity	Cross-linking
Xyloglucan/poloxamer	Tropicamide	Have significantly higher corneal permeation across excised goat cornea, less toxic, and non-irritant	Encapsulation
Wheat gluten	Ethofumesate	Reduce its diffusivity	Entrapment/ extrusion
Alginate	Azadirachtin	Slower release	Encapsulation
Surfactants/oil/water	Glyphosate	Increase in bio-efficacy, alleviating the negative effect of pesticide formulations into environment	Emulsion
Alginate/chitosan	Paraquat	Increased period of action of the chemical on precise targets while reducing problems of ecological toxicity	Pre-gelation of alginate then complexation between alginate and chitosan
Polyhydroxybutyrate-co-hydroxyvalerate	Atrazine	Decreased genotoxicity and increased biodegradability	Encapsulation
Organic-inorganic nano-hybrid	2,4-Dichlorophenoxyacetate	Control release	Self-assembly

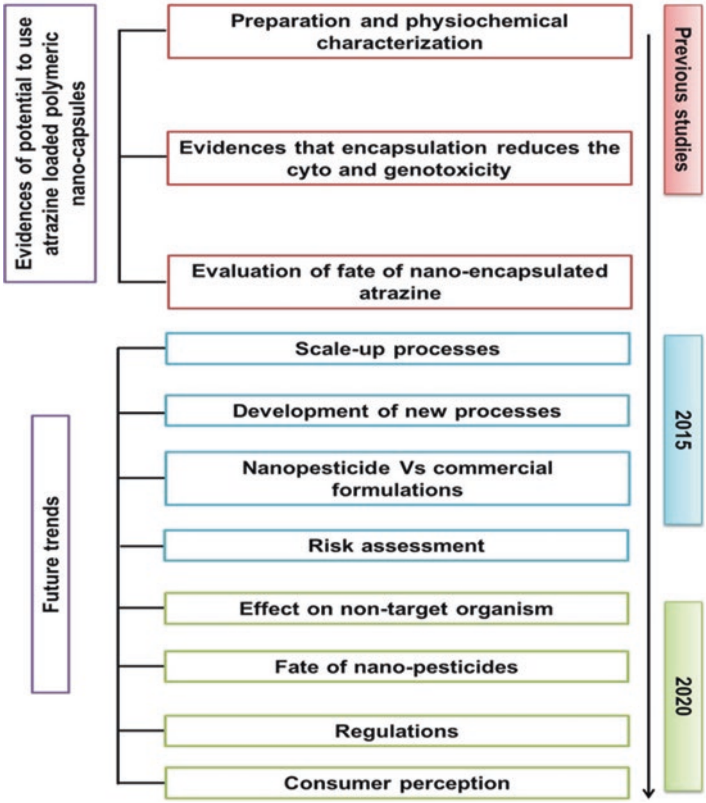

Fig. 2 Timescale for development of atrazine nano-pesticide

progress made in the exploitation of nano-pesticides (such as atrazine) represents a useful case study to identify the main parameters necessary to predict the behavior of nanomaterials in the environment (Grillo et al. 2012) (Fig. 2). In the study of the atrazine-nano-pesticide system, care was taken to understand the mechanisms of interaction with both target, mustard (Oliveira et al. 2015a), and non-target organisms, maize (Oliveira et al. 2015b), and risk assessment analyses were also considered (Kah et al. 2014). However, future case studies are necessary in order to address the safety of workers and consumers with respect to food produced using nanomaterials and nanoparticles. The implementation of nanotechnology in agriculture also requires the development of techniques capable of quantifying engineered nanoparticles at the concentrations present in different environmental compartments (Sadik et al. 2014). Currently available methods are not always adequate to understand the dynamics of nanomaterials in the environment, their interactions with target and non-target organisms, or the occurrence of synergistic effects. These methodological advances allow a life-cycle assessment of the new developed nanomaterials (Parisi et al. 2015). Moreover, studies on methodologies able to evaluate the arise of resistance mechanisms to nanomaterials by certain microorganisms should be undertaken. As a whole, the newly developed analytical methodologies would support predictive models to characterize, localize, and quantify engineered nanomaterials in the environments. In this context, knowledge exchange among scientists from different research fields would be essential (Malysheva et al. 2015). Besides, eco-toxicological research would increasingly focus attention on the environmental consequence of the materials and complexity of natural systems. Extensive research would be necessary to determine delayed impacts of environmental exposure to NPs and to help determine possible adaptive mechanisms (Cox et al. 2017; Singh et al. 2017). More research on bioaccumulation in the food chain and interaction of NPs with other pollutants in the environment should be focused. NPs in plants enter in cellular system; thereby they get translocated through the shoot and are accumulated in various aerial parts of the plant. Also, the possibility of their cycling in the ecosystem increases through various trophic levels. The accumulation of NPs in plants is problematic as it affects various physiological activities of the plant like rate of transpiration, respiration, altering the process of photosynthesis, and interferes with translocation of food materials (Du et al. 2017). The degree of toxicity is linked to this surface and to the surface properties of the NPs. The eco-toxicity of NPs is thus very important as it creates a direct link between the adverse effects of NPs and the organisms including microorganisms, plants, and other organisms including humans at various trophic levels (Tripathi et al. 2016).

11 Recent Developments in Agro-nanotechnology

With nanotechnology gaining recognition in the agricultural and food sectors, scientists have recently showcased their nanotechnology expertise to farmers in Africa. Three significant innovations were demonstrated: the scientists have planned to develop a plastic storage bag lined with nanoparticles that are capable of reacting with oxygen and preventing cassava from rotting. In this way, the African farmers can prolong the shelf life of cassava and prevent wastage of this vegetable. Secondly, milk container was designed with a nano-patterned, antimicrobial coating that helps the dairy farmers in Africa to preserve milk for a prolonged time period as they take almost a whole day to reach the cooling centers. These nanotechnology-based milk containers replace the currently used plain plastic bags. Besides, they have also planned to develop nano-patterned paper sensors to detect bovine pregnancy in order to enable the dairy farmers determine if their cows will run dry without milk due to udder infection or pregnancy (Fraceto et al. 2016; Prasad et al. 2017).

12 Conclusions and Future Perspective

Considering the great challenges we will be facing, in particular due to a growing global population and climate change, the application of nanotechnologies as well as the introduction of nanomaterials in agriculture potentially can greatly contribute to address the issue of sustainability. In fact, the efficient use of fertilizers and pesticides can be enhanced by the use of nano-scale carriers and compounds, reducing the amount to be applied without impairing productivity. Nanotechnologies can also have an impact on the reduction of waste, both contributing to a more efficient production as well as to the reuse of waste, while nanosensors technology can encourage the diffusion of precision agriculture, for an efficient management of resources, including energy (FAO and WHO 2013). However, with the application of all new technologies, there is the need to perform a reliable risk-benefit assessment, as well as a full cost accounting evaluation. In the case of nanotechnologies, this requires also the development of reliable methods for the characterization and quantification of nanomaterials in different matrices and for the evaluation of their impact on the environment (Servin and White 2016) as well as on human health (EFSA Scientific Committee 2011). Furthermore, it is very important to engage all stakeholders, including non-governmental and consumer associations, in an open dialogue to acquire consumer acceptance and public support for this technology.

References

Amenta V, Aschberger K, Arena M, Bouwmeester H, Moniz FB, Brandhoff P et al (2015) Regulatory aspects of nanotechnology in the agri/feed/food sector in EU and non-EU countries. Regul Toxicol Pharmacol 73:463–476

Bellingham BK (2011) Proximal soil sensing. Vadose Zone J 10:1342–1342

Bhattacharyya A, Duraisamy P, Govindarajan M, Buhroo AA, Prasad R (2016) Nano-biofungicides: emerging trend in insect pest control. In: Prasad R (ed) Advances and applications through fungal nanobiotechnology. Springer International Publishing, Cham, pp 307–319

Bulovic V, Mandell A, Perlman A (2004) Molecular memory device. US 20050116256 A1

Campbell BM, Thornton P, Zougmoré R, van Asten P, Lipper L (2014) Sustainable intensification: what is its role in climate smart agriculture? Curr Opin Environ Sustain 8:39–43

Couvreur P, Dubernet C, Puisieux F (1995) Controlled drug delivery with nanoparticles: current possibilities and future trends. Eur J Pharm Biopharm 41:2–13

Cox A, Venkatachalam P, Sahi S, Sharma N (2017) Reprint of: silver and titanium dioxide nanoparticle toxicity in plants: a review of current research. Plant Physiol Biochem 110:33–49

de Medeiros GA, Arruda FB, Sakai E, Fujiwara M (2001) The influence of crop canopy on evapotranspiration and crop coefficient of beans (*Phaseolus vulgaris* L.). Agric Water Manag 49:211–224

de Oliveira JL, Campos EV, Bakshi M, Abhilash PC, Fraceto LF (2014) Application of nanotechnology for the encapsulation of botanical insecticides for sustainable agriculture: prospects and promises. Biotechnol Adv 32:1550–1561

Dixit R, Malaviya WD, Pandiyan K, Singh UB, Sahu A et al (2015) Bioremediation of heavy metals from soil and aquatic environment: an overview of principles and criteria of fundamental processes. Sustainability 7:2189–2212

Du W, Tan W, Peralta-Videa JR, Gardea-Torresdey JL, Ji R, Yin Y et al (2017) Interaction of metal oxide nanoparticles with higher terrestrial plants: physiological and biochemical aspects. Plant Physiol Biochem 110:210–225

EFSA Scientific Committee (2011) Scientific opinion on guidance on the risk assessment of the application of nanoscience and nanotechnologies in the food and feed chain. EFSA J 9:2140

El Beyrouthya M, El Azzi D (2014) Nanotechnologies: novel solutions for sustainable agriculture. Adv Crop Sci Technol 2:e118

Ezhilarasi PN, Karthik P, Chhanwal N, Anandharamakrishnan C (2012) Nanoencapsulation techniques for food bioactive components: a review. Food Bioprocess Technol 6:628–647

FAO (2013) Food Agriculture Organization of the United Nations WHO, World Health Organization. State of the Art on the Initiatives and Activities Relevant to Risk Assessment and Risk Management of Nanotechnologies in the Food and Agriculture Sectors. Technical Paper, FAO and WHO, Rome

Feynman RP (1996) No ordinary genius: the illustrated Richard Feynman. W.W. Norton & Company, New York

Floros JD, Newsome R, Fisher W, Barbosa-Cánovas GV, Chen H, Dunne CP et al (2010) Feeding the world today and tomorrow: the importance of food science and technology. Compr Rev Food Sci Food Saf 9:572–599

Fraceto LF, Grillo R, de Medeiros GA, Scognamiglio V, Rea G, Bartolucci C (2016) Nanotechnology in agriculture: which innovation potential does it have? Front Environ Sci 4:20

Garnett T, Godfray C (2012) Sustainable intensification in agriculture. Navigating a course through competing food system priorities. In: Food climate research network and the oxford martin programme on the future of food. University of Oxford, Oxford

Gibney E (2015) Bucky balls in space solve 100-year-old riddle. Nature News. https://doi.org/10.1038/nature.2015.17987

Grillo R, Dos Santos NZP, Maruyama CR, Rosa AH, De Lima R, Fraceto LF et al (2012) Poly (epsilon-caprolactone) nanocapsules as carrier systems for herbicides: physico-chemical characterization and genotoxicity evaluation. J Hazard Mater 231:1–9

Grillo R, Abhilash PC, Fraceto LF (2016) Nanotechnology applied to bio-encapsulation of pesticides. J Nanosci Nanotechnol 16:1231–1234

Ion AC, Ion I, Culetu A (2010) Carbon-based nanomaterials: environmental applications, vol 38. Univ. Politehn. Bucharest, București, pp 129–132

Kah M, Machinski P, Koerner P, Tiede K, Grillo R, Fraceto LF et al (2014) Analysing the fate of nanopesticides in soil and the applicability of regulatory protocols using a polymer-based nanoformulation of atrazine. Environ Sci Pollut Res Int 21:11699–11707

Kandasamy S, Prema RS (2015) Methods of synthesis of nano particles and its applications. J Chem Pharm Res 7:278–285

Khin MM, Nair AS, Babu VJ, Murugan R, Ramakrishna S (2012) A review on nanomaterials for environmental remediation. Energy Environ Sci 5:8075–8109

Khota LR, Sankarana S, Majaa JM, Ehsania R, Schuster EW (2012) Applications of nanomaterials in agricultural production and crop protection: a review. Crop Prot 35:64–70

Lambreva MD, Lavecchia T, Tyystjärvi E, Antal TK, Orlanducci S, Margonelli A et al (2015) Potential of carbon nanotubes in algal biotechnology. Photosyn Res 125:451–471

Liu R, Lal R (2015) Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions. Sci Total Environ 514:131–139

Malysheva A, Lombi E, Voelcker NH (2015) Bridging the divide between human and environmental nanotoxicology. Nat Nanotechnol 10:835–844

Mishra S, Singh HB (2015) Biosynthesized silver nanoparticles as a nanoweapon against phytopathogens: exploring their scope and potential in agriculture. Appl Microbiol Biotechnol 99:1097–1107

Misra P, Shukla PK, Pramanik K, Gautam S, Kole C (2016) Nanotechnology for crop improvement. In: Kole C, Kumar D, Khodakovskaya M (eds) Plant nanotechnology. Springer, Cham, pp 219–256

Mousavi SR, Rezaei M (2011) Nanotechnology in agriculture and food production. J Appl Environ Biol Sci 1:414–419

Mukhopadhyay SS (2014) Nanotechnology in agriculture: prospects and constraints. Nanotechnol Sci Appl 7:63–71

Nuruzzaman M, Rahman MM, Liu Y, Naidu R (2016) Nanoencapsulation, nano-guard for pesticides: a new window for safe application. J Agric Food Chem 64:1447–1483

Oliveira HC, Stolf-Moreira R, Martinez CBR, Grillo R, De Jesus MB, Fraceto LF (2015a) Nanoencapsulation enhances the post-emergence herbicidal activity of atrazine against mustard plants. PLoS One 10:e0132971

Oliveira HC, Stolf-Moreira R, Martinez CBR, Sousa GFM, Grillo R, De Jesus MB et al (2015b) Evaluation of the side effects of poly(epsilon-caprolactone) nanocapsules containing atrazine toward maize plants. Front Chem 3:61

Ozdemir M, Kemerli T (2016) Innovative applications of micro and nanoencapsulation in food packaging. In: Lakkis JM (ed) Encapsulation and controlled release technologies in food systems. Wiley, Chichester

Parisi C, Vigani M, Rodriguez-Cerezo E (2015) Agricultural nanotechnologies: what are the current possibilities? Nano Today 10:124–127

Pirzadah TB, Malik B, Maqbool T, Rehman RU (2019) Development of nano-bioformulations of nutrients for sustainable agriculture. In: Prasad R, Kumar V, Kumar M, Choudhary D (eds) Nanobiotechnology in bioformulations. Springer, Cham, pp 381–394. Nanotechnology in the Life Sciences

Prasad R, Kumar V, Prasad KS (2014) Nanotechnology in sustainable agriculture: present concerns and future aspects. Afr J Biotechnol 13(6):705–713

Prasad R, Pandey R, Barman I (2016) Engineering tailored nanoparticles with microbes: quo vadis. Wiley Interdiscip Rev Nanomed Nanobiotechnol 8:316–330

Prasad R, Bhattacharyya A, Nguyen QD (2017) Nanotechnology in sustainable agriculture: recent developments, challenges, and perspectives. Front Microbiol 8:1014. https://doi.org/10.3389/fmicb.2017.01014

Ravichandran R (2010) Nanotechnology applications in food and food processing: innovative green approaches, opportunities and uncertainties for global market. Int J Green Nanotechnol Phys Chem 1(2):P72–P96

Rodríguez J, Martín MJ, Ruiz AM, Clares B (2016) Current encapsulation strategies for bioactive oils: from alimentary to pharmaceutical perspectives. Food Res Int 83:41–59

Sabir S, Arshad M, Chaudhari SK (2014) Zinc oxide nanoparticles for revolutionizing agriculture: synthesis and applications. Sci World J 2014:8

Sadik OA, Du N, Kariuki V, Okello V, Bushlyar V (2014) Current and emerging technologies for the characterization of nanomaterials. ACS Sustain Chem Eng 2:1707–1716

Sagadevan S, Periasamy M (2014) Recent trends in nano-biosensors and their applications - a review. Rev Adv Mater Sci 36:62–69

Scognamiglio V (2013) Nanotechnology in glucose monitoring: advances and challenges in the last 10 years. Biosens Bioelectron 47:12–25

Scognamiglio V, Arduini F, Palleschi G, Rea G (2014) Biosensing technology for sustainable food safety. Trac-Trends Anal Chem 62:1–10

Sekhon BS (2014) Nanotechnology in Agri-food production: an overview. Nanotechnol Sci Appl 7:31–53

Sertova NM (2015) Application of nanotechnology in detection of mycotoxins and in agricultural sector. J Cent Eur Agric 16:117–130

Servin AD, White JC (2016) Nanotechnology in agriculture: next steps for understanding engineered nanoparticle exposure and risk. Nano Impact 1:9–12

Singh S, Vishwakarma K, Singh S, Sharma S, Dubey NK, Singh VK et al (2017) Understanding the plant and nanoparticle interface at transcriptomic and proteomic level: a concentric overview. Plant Gene 11(Part B):265–272. https://doi.org/10.1016/j.plgene.2017.03.006

The Royal Society (2009) Reaping the benefits: science and the sustainable intensification of global agriculture. The Royal Society, London

Thornhill S, Vargyas E, Fitzgerald T, Chisholm N (2016) Household food security and biofuel feedstock production in rural Mozambique and Tanzania. Food Secur 8:953–971

Tripathi DK, Shweta, Singh S, Singh S, Pandey R, Singh VP et al (2016) An overview on manufactured nanoparticles in plants: uptake, translocation, accumulation and phytotoxicity. Plant Physiol Biochem 110:2–12

Valdes MG, Gonzalez ACV, Calzon JAG, Diaz-Garcia ME (2009) Analytical nanotechnology for food analysis. Microchim Acta 166:1–19

Vanderroost M, Ragaert P, Devlieghere F, De Meulenaer B (2014) Intelligent food packaging: the next generation. Trends Food Sci Technol 39:47–62

Vartholomeos P, Fruchard M, Ferreira A, Mavroidis C (2011) MRI-guided nanorobotic systems for therapeutic and diagnostic applications. Annu Rev Biomed Eng 13:157–184

Vidotti M, Carvalhal RF, Mendes RK, Ferreira DCM, Kubota LT (2011) Biosensors based on gold nanostructures. J Braz Chem Soc 22:3–20

Viswanathan S, Radecki J (2008) Nanomaterials in electrochemical biosensors for food analysis- a review. Pol J Food Nutr Sci 58:157–164

Yao J, Yang M, Duan YX (2014) Chemistry, biology, and medicine of fluorescent nanomaterials and related systems: new insights into biosensing, bioimaging, genomics, diagnostics, and therapy. Chem Rev 114:6130–6178

Yunlong C, Smit B (1994) Sustainability in agriculture: a general review. Agric Ecosyst Environ 49:299–307