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Review

Nanotechnologies in agriculture: New tools for sustainable development

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Nanoscale science and nanotechnology have been demonstrated to have great potential in providing novel and improved solutions to many grand challenges facing agriculture and society today and in the future. This review highlights some of the most promising and important nanotechnology applications in agriculture; and recommends several strategies for advancing the best scientific and technological knowledge presently being examined. In addition, implications for human and environmental health, and technical, financial and capacity-related challenges as they relate to developing countries are identified. Finally, some suggested mechanisms for partnerships and collaborations are also identified and suggested.

Science and technology in agriculture: opportunities and challenges for the developing world

Presently, the agricultural sector is facing various global challenges: climate change, urbanization, sustainable use of resources, and environmental issues such as run-off and accumulation of pesticides and fertilizers. These situations are further exacerbated by the growing food demand that will be needed to sustain an estimated population growth from the current level of about 6 billion to 9 billion by 2050. In addition, considering the world's diminishing petroleum resources, agricultural products and materials will soon be viewed again as the foundation of commerce and manufacturing, hence additional demands on agricultural production. At the same time there are new opportunities emerging. For example, the use of agricultural waste for the generation of energy and electricity could be a viable solution pending workable economics and encouraging policy. This aforementioned scenario of rapidly evolving and yet complex agriculture system is, and will pose even greater challenges to developing countries. The agricultural sector and commodity production in developing regions are the backbone of the national economy where multitude critical issues such as lack of new arable soil, reduction of the current agricultural land due to competing economic development activities, commodity dependence, poverty and malnutrition are closely intertwined.

Over the last several decades, the rapid growth in technological innovations have led to profound structural changes in the agricultural sector, including a transition from smallholder mixed farms toward large-scale specialized industrial production systems, a shift in the geographic locus of demand and supply to the developing world, and an increasing emphasis on global sourcing and marketing. The latter present challenges to the agricultural sector to provide possible improvements to its production sustainability in ways that promote food security, poverty reduction and public health improvement.

Advances in science and technology could offer potential solutions for developing countries to innovate and add value to their current commodities production systems. Many technologies being developed have the potential not only to increase farm productivity but also to reduce the environmental and resource costs often associated with agricultural production. These include technologies that conserve land and water by increasing yields with the same or fewer inputs and technologies that protect environmental quality. It will be crucial, however, to support these applications even though they may not be commercially lucrative while avoiding the risk that some advances in science and technology may increase the disparity between developed and developing

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countries. Therefore, serious consideration of the social and ethical implications on new agriculture technologies will be necessary. It should also be recognized that while new agri-food technologies may deliver efficiencies in some areas, they may not necessarily solve existing problems of global food production and distribution. In this regard it is essential for developing countries to actively participate in research and development while respecting their needs and capacity to utilize these new technologies. Therefore, critical to the innovation, capacity building is the establishment of relevant, complementary and synergistic partnerships between developing countries and more advanced countries.

Nanotechnologies in future agriculture

Nanoscale science, engineering and technology embrace an exciting and broad scientific frontier which will have significant impacts on nearly all aspects of the global economy, industry, and people's life in the 21st century (Gruère, Narrod, & Abbott, 2011; Scott & Chen, 2003). Nanoscale sciences reveal the properties, processes, and phenomena of matters at the nanometer (1 to approximately 100 nm) range. Nanoscale engineering renders precise capability to control and/or fabricate matters at this scale to render novel and useful properties thus leading to many new applications of nanoscale science and nanomaterials that can be used to address numerous technical and societal issues.

In this section, some potential applications of nanoscale science, engineering and nanotechnology for agriculture and food production and related issues are discussed. Despite a wide-range of industrial interest in this area, examples of available commercial products are few. Most applications are either in research and development (R&D) pipeline or at bench-top exploration stage; however, it is likely that the agriculture and food sector will see some large-scale applications of nanotechnologies in the near future. Some current industrial examples are indicated in the sections below.

Nanotechnologies in plant-based agricultural production and products

Plant-based agricultural production is the basis of broad agriculture systems providing food, feed, fiber, fire (thermal energy), and fuels through advancements in materials sciences, and biomass conversion technologies. While the demand for crop yield will rapidly increase in the future, the agriculture and natural resources such as land, water and soil fertility are finite. Other production inputs including synthetic fertilizers and pesticides are predicted to be much more expensive due to the constraints of known petroleum reserve. Precision farming is hence an important area of study to minimize production inputs and maximize agricultural production outputs for meeting the increasing needs of the world sustainability. Given that nanotechnology may allow for the precise control of manufacturing at the nanometer scale, a number of novel possibilities in elevating the precision farming practices are possible.

- *Nanotechnology enabled delivery of agriculture chemicals (fertilizers, pesticides, herbicides, plant growth regulators, etc.)*: Many nanoscale carriers, including encapsulation and entrapment, polymers and dendrimers, surface ionic and weak bond attachments and other mechanisms may be used to store, protect, deliver, and release by control of intended payloads in crop production processes. One of the advantages of nanoscale delivery vehicles in agronomic applications is its improved stability of the payloads against degradation in the environment, thereby increasing its effectiveness while reducing the amount applied. This reduction helps address agricultural chemicals run-off and alleviate the environmental consequence. The nanoscale delivery vehicles may be designed to "anchor" to plant roots or the surrounding soil structures and organic matter if molecular or conformational affinity between the delivery nanoscale structure and targeted structures and matters in soil could be utilized (Johnston, 2010). Controlled release mechanisms allow the active ingredients to be slowly taken up, hence, avoiding temporal overdose, reducing the amount of agricultural chemicals used, and minimizing the input and waste. Environmental consideration including precision farming can reduce pollution to a minimum.
- *Field sensing systems to monitor the environmental stresses and crop condition*: Nanotechnology may be developed and deployed for real time monitoring of the crop growth and field conditions including moisture level, soil fertility, temperature, crop nutrient status, insects, plant diseases, weeds, etc. Networks of wireless nanosensors positioned across cultivated fields provide essential data leading to best agronomic intelligence processes with the aim to minimize resource inputs and maximizing output and yield (Scott & Chen, 2003). Such information and signals include the optimal times for planting and harvesting crops and the time and level of water, fertilizers, pesticides, herbicides, and other treatments that need to be administered given specific plant physiology, pathology, and environmental conditions.
- *Nanotechnology enables the study of plant disease mechanisms*. The advancement in nanofabrication and characterization tools have enabled studies of physical, chemical and biological interactions between plant cell organelles and various disease causing pathogens, i.e., plant pathology. A better understanding of plant pathogenic mechanisms such as flagella motility and biofilm formation will lead to improved treatment strategies to control the diseases and protect production (Cursino *et al*., 2009). For example, spatial and temporal studies of plant pathogenic xylem inhabiting bacteria have traditionally been conducted by monitoring changes in bacterial populations through destructive sampling techniques of tissues at various distances from inoculation sites. This approach seriously limits the information that can be obtained regarding colonization, biofilm development, and

subsequent movement and re-colonization at new areas, primarily because the same region or sample site cannot be followed temporally. Micro-fabricated xylem vessels with nano-size features have been shown very useful in gaining an appreciation of the mechanisms and kinetics of bacterial colonization in xylem vessels such that novel disease control strategies may be developed (Zaini, De La Fuente, Hoch & Burr, 2009).

- *Improving plant traits against environmental stresses and diseases:* Biotechnological research has been focusing on improving plant resilience against various environmental stresses such as drought, salinity, diseases, and others. Genomes of crop cultivars are currently being extensively studied. The advancement in nanotechnology-enabled gene sequencing is expected to introduce rapid and cost effective capability within a decade (Branton *et al.*, 2008), hence leading to more effective identification and utilization of plant gene trait resources.
- *Lignocellulosic nanomaterials*: Recent studies have shown that nanoscale cellulosic nanomaterials can be obtained from crops and trees. It opens up a whole new market for novel and value-added nano biomaterials and products of crops and forest. For example, cellulosic nano crystals can be used as light weight reinforcement in polymeric matrix as nanocomposite (Laborie, 2009; Mathew, Laborie, & Oksman, 2009). Such applications may include food and other packaging, construction, and transportation vehicle body structures. A consortium led by North Dakota State University (NDSU) is currently engaged in a project to commercialize a cellulosic nano whisker production technology, developed by Michigan Biotechnology Incorporate (MBI) International, from wheat straw. The cellulosic nano whiskers (CNW) would then be used to make biocomposites that could substitute for fiberglass and plastics in many applications, including automotive parts (Leistritz *et al*., 2007).

As indicated earlier, nanosized agricultural chemicals are mainly still at the research and developmental stage. Natural Nano, a start-up company in Rochester, N.Y., has found a way to use Halloysite, a naturally found clay nanotube, as a low cost delivery for pesticides to achieve an extended release and better contact with plants. It is estimated that using this technology could reduce the amount of pesticides applied by 70 or 80 percent, a significant reduction in quantity and cost of pesticides as well as less impact on water streams (Murphy, 2008).

Developing countries like China have been aggressively developing nanotechnology based delivery of agricultural chemicals. These technologies are expected to be deployed for field applications in next 5−10 years. The success of broad applications of nanoscale agricultural chemicals in crop production will largely depend on market demands, profit margin, environmental benefits, risk assessment and management policy in the background of other competitive technologies.

Nanotechnologies in animal production and animal health

Agriculturally relevant animal production (livestock, poultry, and aquaculture) provides society with highly nutritious foods (meat, fish, egg, milk and their processed products) which have been, and will continue to be, an important and integral part of human diets. There are a number of significant challenges in animal agricultural production, including production efficiency, animal health, feed nutritional efficiency, diseases including zoonoses, product quality and value, by-products and waste, and environmental footprints. Nanotechnologies may offer effective, sometimes novel, solutions to these challenges (Kuzma, 2010).

- *Improving feeding efficiency and nutrition of agricultural animals*: A critical element of sustainable agricultural production is the minimization of production input while maximizing output. One of the most significant inputs in animal production is feedstock. Low feeding efficiency results in high demand of feed, high discharges of waste, heavy environmental burden, high production cost, and competing with other uses of the grains, biomass, and other feed materials. Nanotechnology may significantly improve the nutrient profiles and efficacy of minor nutrient delivery of feeds. Most animal feeds are not nutritionally optimal, especially in developing countries. Adding supplemental nutrients is an effective approach to improve the efficiency of protein synthesis and the utilization of minor nutrients. Other digestive aids such as cellulosic enzymes can facilitate better utilization of the energy in plant-based materials. Furthermore, minor nutrients and bioactives can help improve overall health of animals so that an optimal physiological state can be achieved and maintained. A variety of nanoscale delivery systems have been investigated for food applications. They include micelles, liposomes, nano-emulsions, biopolymeric nanoparticles, protein-carbohydrate nanoscale complexes, solid nano lipid particles, dendrimers, and others. These systems collectively have shown numerous advantages including better stability against environmental stresses and processing impacts, high absorption and bioavailability, better solubility and disperse-ability in aqueous based systems (food and feed), and controlled release kinetics (Chen, Weiss, & Shahidi, 2006). Self assembled and thermodynamically stable structures require little energy in processing thereby helping to address issues related to sustainability. Nanoscale delivery can be used to improve the nutritional profiles of feed and feeding efficiency. In addition, the nanoscale delivery systems can also be designed for veterinary drug delivery which protects the drug in GI tract, and allows for release at the desired location and rate for optimal effect. These advantages help improve the efficiency by which animals utilize nutrient resources, reduce material and financial burden of the producers, and improve product quality and production yield. Similar to food applications, the design of an appropriate nanoscale delivery system will require a full consideration of the effectiveness of its intended uses while preventing any adverse effects or unintended consequences. The nanoscale particles should be subject to a rigorous risk assessment to ensure responsible and safe development and deployment in the products.

- *Minimizing losses from animal diseases, including Zoonoses*: Many animal diseases cause substantial losses in agricultural animal production. Some of the more significant diseases include bovine mastitis, tuberculosis, respiratory disease complex, Johne's disease, avian influenza, and porcine reproductive and respiratory syndrome (PRRS). The World Health Organization (WHO) estimates that animal diseases represent as much as 17 percent of animal production costs in the developed world, and more than twice this figure in developing nations. On average, one newly identified animal infectious disease has emerged each year for the past 30 years of which approximately 75 percent have been zoonotic (e.g., mad cow disease; Avian influenza; H1N1 Influenza; Ebola virus; Nipah virus) (WHO, 2005). Zoonotic diseases not only cause devastating economic losses to animal producers, but also impose serious threats to human health, e.g., Variant Creutzfeldt-Jakob Disease (vCJD). Detection and intervention are two important tools of an integrated animal disease management strategy that is critical to significantly reducing losses/threats from the disease, and/or eradicating disease, or preventing disease introduction into the animal production. Nanotechnology has the potential to enable revolutionary changes in this area, and some specific technologies may be feasible in near future given the current state of research and development (Emerich & Thanos, 2006; Scott, 2007). Nanotechnology offers numerous advantages in detection and diagnostics including high specificity and sensitivity, simultaneous detection of multiple targets, rapid, robust, on-board signal processing, communication, automation, convenient to use, and low cost. The uses of portable, implantable or wearable devices are particularly welcome in agricultural field applications. Early detection is imperative so that quick, simple and inexpensive treatment strategies can be taken to remedy the situation. Nanotechnology based drugs and vaccines can be more effective in treating/preventing the diseases than current technologies, thus reducing cost. Precise delivery and controlled release of nanotechnology enabled drugs leave little footprint in the animal waste and the environment, which alleviate the increasing concern of antibiotic resistance, and decrease health and environmental risks associated with the use of antibiotics. The targeted delivery and active nanoparticles may enable new drug administrations that are convenient, fast, non-intrusive to animals, and cost effective. Theragnostics – a new generation of smart treatment combining diagnostics and therapy in a single step via nanotechnology – will further improve disease treatment efficiency and cost, and eliminate the diseases at early stage, even pre-clinically (Morris, 2009). The effectiveness of new drug delivery technology platforms must first be established using pharmacokinetic and pharmacodynamic studies *in vivo* to investigate the relationship between dose, drug concentration at the site of action, and drug response. Only then can a new drug delivery system be deployed. Research and development for dealing with zoonotic diseases should collaborate with expertise from the human and veterinary medical communities for a more effective advancement.
- *Animal reproduction and fertility*: Animal reproduction remains a challenge not only in developing countries, but also in developed nations. Low fertility results in low production rate, increases in financial input, and reduced efficiency of livestock operations (Narducci, 2007). Several technological fronts have been explored in order to improve animal reproduction. Microfluidic technology has matured over the last two decades, and has been integrated into many nanoscale processing and monitoring technologies including food and water quality, animal health, and environmental contaminations. The development of efficient microfluidic technology has enabled the automated production of large numbers of embryos *in vitro*, which has led to the rapid development of genetic improvement and selection of superior livestock for human food and fiber production (Raty *et al*., 2004). Brazilian animal scientists have used Fixed-Time Artificial Insemination (FTAI) technology to effectively increase the cattle reproduction rate for many years. However, the technology depends on the regulation of progesterone administered through a silicone matrix. The procedure has substantial drawbacks including inefficient and irregular dispersion of hormone, disposal issues, being labor intensive, and requiring multiple animal handlings for each attempt. Nanoscale delivery vehicles are sought to substantially improve bioavailability and better control of release kinetics, reduce labor intensity, and minimize waste and discharge to the environment (Emerich & Thanos, 2006; Narducci, 2007). Another strategy that may be explored is to monitor animal hormone level using implanted nanotechnology-enabled sensing device with wireless transmission capability, thus the information of optimal fertility period can become available in real time to assist the livestock operators for reproduction decision making (Afrasiabi, 2010).
- *Animal product quality, value and safety*: Modification of animal feeds has been effectively used to improve animal production as well as product quality and value. The regulation of nutrient utilization can be used to enhance the efficiency of animal production, and to design animal-derived foods consistent with health recommendations and consumer perceptions. For example, the concepts of nutrient regulation have been used to redesign foods, such as milk fatty acids, *cis*-9, *trans*-11 conjugated linoleic acid (CLA) and vaccenic acid (VA), that may have a potential role in the prevention of chronic human diseases such as cancer and atherogenesis (Bauman, Perfield, Harvatine, & Baumgard, 2008). The biosynthesis and concentration

of CLA and VA in milk fat of lactating ruminants may be enhanced and efficiently controlled by nanotechnology enabled delivery of nutrients. Collaborative research examining the biological benefits of functional foods with enhanced CLA/VA content in biomedical studies with animal models of human diseases and in human clinical using biomarkers for chronic disease could benefit from new technologies based on nanotechnology capabilities. Biomarker triggered release mechanisms may be explored for new discoveries of nanoscale structural actions. Biotechnology has also been explored in animal and food product quality. Nanotechnology research is attempting to sequence a mammalian genome in less than 24 h and less than $1000 (Branton *et al*., 2008). Once this technical capability becomes available in the next decade, the pace of biotechnology research and development will be substantially accelerated.

- *Turning animal by-products and waste and environmental concerns into value added products*: Animal waste is a serious concern in the animal production industry. Stricter environmental policies will prevent irresponsible discharge of animal waste. The unpleasant odors that emanate from intensive animal production facilities adversely affect air quality, and in turn, living conditions and the real estate value of the adjacent area. However, bioconversion of animal waste into energy and electricity can result in new revenue, renewable energy, high quality organic fertilizer, and improved environmental quality while value added (Scott, 2002). Nanotechnology-enabled catalysts will play a critical role in efficient and cost effective bioconversion and fuel cell for electricity production as well as enabling efficient energy storage which will greatly facilitate and benefit the development of distributed energy supplies, especially in rural communities where infrastructure is lacking (Davis *et al*., 2009; Soghomonian & Heremans, 2009). Such an approach may result in the elimination of the need for system wide electricity grids, hence accelerate the rural development and improve productivity, and business and living environment and will be especially beneficial to developing countries.

Nanotechnologies for water quality and availability

Providing clean and abundant fresh water for human use and industry applications, including agricultural and farming uses, is one of the most daunting challenges facing the world (Vörösmarty *et al*., 2010). It is estimated that "more than one billion people in the world lack access to clean water, and the situation is getting worse. Over the next two decades, the average supply of water per person will drop by a third, possibly condemning millions of people to an avoidable premature death." (Savage, Diallo, Duncan, Street, & Sustich, 2009). Agriculture requires considerable amount of fresh water, and in turn, often contributes substantially to pollution of groundwater through the use of pesticides, fertilizers and other agricultural chemicals. Effective technologies for remediation and purification will be needed to manage the volume of wastewater produced by farms on a continual basis, and be cost effective for all.

Technical issues in the water challenges include water quality and quantity, treatment and reuse, safety due to chemical and biological hazards, monitoring and sensors. Nanotechnology R&D has shown great promises in providing novel and economically feasible solutions. Several aspects of nanotechnology solutions are briefly discussed below.

Water quantity, quality and safety — treatment, decontamination, reuse, and conservation

Accessible water resources are often contaminated with pollutants largely due to various human activities, but also natural leaching. These contaminants include, but not limited to, water-borne pathogenic microorganisms (*Cryptosporidium*, Coliform bacteria, virus, etc.), various salts and metals (copper, lead, arsenic, etc.), run-off agricultural chemicals, tens of thousands of compounds considered as pharmaceuticals and personal care products (PPCP), and endocrine disrupting compounds (EDC), and radioactive contaminants either naturally occurring or the result of oil and gas production as well as mining activities. For drinking water, sensory attributes (taste, smell, and turbidity) are also important quality indicators. Various nanoscale tools have been explored to address these challenges to improve water quality and safety. The following sections will give a brief introduction of some of the important developments. For more comprehensive coverage of nanotechnology applications in water, please refer to the paper by Dr. P. Alvarez in this special issue.

- *Microbial disinfection*: In industrialized nations, chemical and physical based (chlorine dioxide, ozone, and ultraviolet) microbial disinfection systems are commonly used. However, much of the world still does not have the industrial infrastructure necessary to support chemical-based disinfection of water. Hence, alternative technologies that require less intensive infrastructure and more cost effective approaches such as nanoscale oligodynamic metallic particles, those may exhibit a toxic effect on living cells even in relatively low concentrations, may be worthy of attention. Among the oligodynamic metallic nanoparticles, silver is considered the most promising nanomaterials with bactericidal and viricidal properties owing to its wide-range effectiveness, low toxicity, ease of use, its charge capacity, high surface to volume ratios, crystallographic structure, and adaptability to various substrates (Nangmenyi & Economy, 2009). Its antimicrobial mechanism is due to the production of reactive oxygen species (ROS) that cleaves DNA. Another nanoscale technological development for microbial disinfection is visible light photocatalysts of transition metal oxides made into nanoparticles, nanoporous fibers, and nanoporous foams (Li, Wu, & Shang, 2009). In addition to its effectiveness in disinfecting microorganisms, it can also remove organic contaminants such as PPCPs and EDCs. Tubular nanostructures may be embedded into microbial cell wall to disrupt its structure integrity and result in leakage of intracellular compounds, and eventually cell death.

- *Desalination:* Given the limited fresh water supplies both above or underground, it is likely that the desalination of sea water will become a major source of fresh water. Conventional desalination technology is reverse osmosis (RO) membranes which generally require large amounts of energy. A number of nanotechnologies have been attempted to develop low energy alternatives. Among them, the 3 most promising technologies appear to be protein-polymer biomimetic membranes, aligned-carbon nanotube membranes, and thin film nanocomposite membranes (Hoek & Ghosh, 2009). Some of the prototypes have demonstrated up to 100 times better water permeability with nearly perfect salt rejection than RO. Carbon nanotube membranes, owing to its extremely high water permeability than other materials of similar size, have desalination efficiencies in the order of thousand times better than the current technology. Some of these membranes can also integrate other functionalities such as disinfection, de-odouring, de-fouling, and self-cleaning. Technical challenges such as scale-up fabrication, practical desalination effectiveness, and long-term stability must be addressed before becoming successfully commercialized. Some of the above mentioned technologies are currently in commercial development stage, which may be introduced in the market place in near future.
- *Removal of heavy metals*: Functionalization of ligand-based nanocoating which is bonded to the surface of high surface and low cost filtration substrate can effectively absorb high concentrations of heavy metal contaminants. The system can be re-generated *in situ* by treatment with bifunctional self-assembling ligand of the previously used nanocoating media. A start-up company (Crystal Clear Technologies) has demonstrated that multiple layers of metal can be bonded to the same substrate (Farmen, 2009). Such a water treatment unit should be available in near future for removal of various heavy metals in water. Another approach to remove heavy metals and ions is the use of dendrimer enhanced filtration (DEF) (Diallo, 2009). Functionalized dendrimers can bind cations and anions according to acidity.

Water conservation in agricultural crop production

The fact that crop production requires large amounts of water has resulted in the implementation of policy and regulations in limiting agricultural production in many regions. Scientists and engineers have been working to improve water usage conservation in agricultural productions. For example, drip irrigation has been developed to conserve water. This innovation has moved precision agriculture in water usage to a much higher level of control than other irrigation technologies such as flood irrigation. New and innovative ideas will likely result in the development of more precise water delivery systems. Future technology platforms should consider the following: water storage, *in situ* water holding capacity, water distribution near roots, water absorption efficiency of plants, encapsulated water released on demand, interaction with field intelligence through distributed nanosensor systems, among others (Savage *et al.*, 2009).

Detection and sensing for pollutants and impurity

Nanotechnology based sensing and the detection of various contaminants in water has been topical over the last decade. Detection level is generally at parts per billion (ppb) for metals and organic contaminants in both laboratory and field applications. The state of science and prototyping for sensing and devices is among the most advanced in the field of nanotechnology, hence it is expected that many new technologies will be readily available in the next decade. Sensor applications for water bear many similarity to other applications, hence are not repeated here. For the general discussion on nanomaterials based biosensors, please refer to the paper by Dr. A. Merkoci in this special issue for more details.

Nanotechnology for the keeping quality and distribution of agricultural and food products

Many agricultural products are either perishable or semi-perishable. These include fresh vegetables, fruits, meats, egg, milk and dairy products, many processed foods, nutraceuticals and pharmaceuticals. The improvement of shelf-life is one of the main areas for nanotechnology research to enhance the ability to preserve the freshness; quality and safety (see the paper by Dr. Q. Chaudhry in this special issue).

Nanotechnology and traceability

A number of factors contribute to an increased demand for the traceability of foods throughout production, processing, distribution and consumption. Food safety outbreaks frequently resulted in wide spread product recalls. Advanced and improved product traceability is essential to ensure food safety by removing all the tainted products in the market and the system during the recall process. Also, product authenticity has seen an increased value in food marketing throughout the world by validating the origin, and therefore, adding to the unique inherent value proposition of the products.

Traceability must meet the following five essential technical challenges (Nightingale, 2008):

1. Have sufficient vocabulary to distinguish all products
2. Not compromise the products
3. Have the same service life as the marked products
4. Easy to read by machines (speed, reliability, and convenience)
5. Should be very inexpensive for food and agricultural products

In response to this market-driven requirement, several systems have been developed to provide consumers with information about the origin of agricultural products and the practices used to produce those products. Luo and his group at Cornell University have developed nucleic acid engineered nanobio barcode technology (Li, Cu, & Luo, 2005) which can address all the five requirements discussed above. The technology has been tested in identifying complicated non-point pollution sources in underground hydrological pathways. It has potential to be used in foods and many other traceability applications.

Nanotechnology based tracing devices can integrate multiple functional devices that provide other important information such as sensors for detection of the presence of pathogens, spoilage microorganisms, allergens, chemicals, and other contaminants in food as well as nutritional information. Additionally, nanoscale tagging devices can be used to record and retrieve information about the product history. These types of applications will aid producers, retailers and consumers regarding food safety, food quality, nutritional values, and others to assist informed decision making processes.

A challenge in new technology development is to manage the cost to be acceptable for its intended use. The inability to manage the cost will pose substantial barriers for many developing countries in producing, using and exporting their products. Fortunately, an inherent advantage of precise nanomanufacturing is the minimal use of materials which may reduce the production cost. The details in economics need to be worked out for actual cases of nanotechnology applications for the intended markets.

Nanotechnologies and clean energy

Access to inexpensive, safe and renewable energy is of utmost importance for worldwide sustainable development. Flexible and efficient, yet inexpensive solar cells are often highlighted as one of the most exciting areas of nanotechnology application in agriculture, as often expressed as "green nanotechnology." Inexpensive systems of solar-powered electricity have long been an aspiration for tropical countries, but glass photovoltaic panels remain too expensive and delicate. Nanotechnology based photovoltaic currently is a high priority of research worldwide, including most industrialized countries. Solar energy conversion to electricity, energy storage, and other nanotechnology-enhanced solar-thermal energy conversion systems are presently active areas of research and development. Cost reduction in photocatalysts and energy materials will be critical. As the research and development advances, the economic feasibility and hurdles of photovoltaic technologies will become clearer; hence strategies may be developed to properly address them. More and more "out-of-box" ideas will continue to emerge. Jennings and Cliffel at Vanderbilt University have explored the use of photosynthesis protein units from leafy vegetables and plants for direct conversion of solar energy to electricity, and have made substantial technical breakthrough (Ciesielski *et al.*, 2010). The current prototype can produce a voltage comparable to that of an AA battery and can remain functional for about 1 year. The most expensive component of this system is the glass microscope slide that serves as the cell base (∼30 ¢). Harnessing solar energy will be a grand challenge that benefits humanity, hence the pursuit will likely be persistent and intensified in years ahead.

Nanotechnology can also contribute to conversion of biomass for fuels, chemical intermediates, speciality chemicals and products. As biomass becomes an increasingly important industrial feedstock, a new generation of catalysts to reduce production cost while being economically feasible will be critical. Nanostructures have the inherent advantage as catalysts of their large surface area per unit volume, and the capability to precisely control composition, structure, functionalization, and other important properties of catalysts (Davis *et al.*, 2009).

Governance and policies for fair and sound technological development

Nanotechnology, as has been commonly defined, i.e., the science and engineering at the intermediate length scale of 1 to approximately 100 nm, has been actively pursued globally for about ten years. While many advances have been made, the development has been inconsistent across scientific areas and geographic regions. In agriculture, the research is still in its early stage. While the potential for many beneficial applications have been demonstrated at concept and bench-top, greater efforts are still required for commercialization. At the same time, research on methodology, identification and characterization of nanomaterials, testing priorities and regulatory guidance on nanoparticle safety are still in their infancy. Increased research in potential risk assessment for responsible development by all the stakeholders will be required in order to advance the field. Private-public partnership (PPP) will also be necessary in order for substantive contributions and advancements to be made in nanotechnology development. It will be mandatory that the public be engaged to ensure a transparent and constructive discussion of the various issues.

Good governance for nanotechnology applications in agriculture and food systems should be discussed and established on important issues including sustained financial investment in nanotechnology research and development, technology transfer models, intellectual properties, and efforts to understand and facilitate technology adoption and sharing among industrialized and technologically disadvantage countries. The International Food Policy Research Institute recently published a policy briefing that offers a number of suggestions worthy of consideration and further discussion (Gruère *et al.*, 2011).

Addressing the above issues in relation to nanotechnology innovation and development requires:

- Enhancing the role of developing countries in responsible nanotechnology development;
- Encouraging the development of appropriate products targeted to help meet critical human health, nutritional and societal needs;

– Including methods for addressing the safety, appropriateness, accessibility and sustainability of nanotechnology to meet the needs of developing countries.

Need for partnerships and collaborations for sustainable agriculture development

Nanotechnology by its very nature will require, and has required, a high degree of multidisciplinary and cross-sector collaboration within and between academic researchers, industry and government. Applications of nanotechnology involves many disciplines in engineering and the natural sciences, including such disciplines as physics, chemistry, biology, materials sciences, instrumentation, metrology, and others. As nanotechnology progresses from discovery to potential applications, it will require a number of tools for visualization, characterization, and fabrication, as well as methods for reproducing and controlling properties, scalability, and cost. These tools and techniques, too, are typically rooted in multiple disciplines.

Despite the progress that has been made in developing countries with strong research capacity building efforts, many of these countries continue to work on filling critical gaps in research infrastructure through contact and access to international research and development networks. It will, therefore, be important to undertake an evaluation of possible collaboration and partnership mechanisms either between public and private or between developed and developing countries in order to meet global demands and expectations. Several developing countries have already been investing strategically and conducting research in nanotechnology applications for agriculture and food systems (Gruère *et al.*, 2011). In particular, Brazil, China, India, and South Africa have been noted for their significant investments in nanotechnology research and development and the development of national nanotechnology strategies focusing on areas of national interest including energy, health, water treatment, agriculture, and the environment.

The combination of public-private-sector partnerships and developed-developing countries collaborations will be useful in achieving new goals in agricultural development ultimately resulting in mutual and global benefits. In doing so, there are some key aspects that need particular attention:

– Exploring new ways of working with the agriculture industry by developing alternative activities that are of benefit to industry and the country where the industry operates.
– Developing and promoting regulations that can stimulate private-sector research in fields of common interests both to the public and to the industry. For example, incentives attempting to protect the environment, food safety, and nutrition may encourage research on technologies that are more compatible with social as well as business goals.
– Education and workforce training are essential in enhancing scientific capabilities in all nations. Numerous courses, workshops and conferences are organized by academia, professional societies, governments, and private entities. Young scientists and students should take the advantage of these offerings to acquire new knowledge and skills required to be proficient workers and researchers in nanotechnology. One of the most recent examples is the International Conference of Food Applications of Nanoscale Science (ICoFANS) held in Tokyo from June 8–10, 2010. A number of graduate students and young scientists from developing countries participated to learn from plenary session presentations, presenting their research posters, and interacting with the leading scientists from around the world. A greater emphasis should be placed to making educational opportunities more easily accessible to people in developing countries throughout the world. The future conference planning should consider meeting locations in developing countries to ease the burden of travel costs of the participants, especially for young scientists and students. The conference operational budget planning should also consider reduced registration fees and travel assistance scholarships to the participants. Internet based educational offering has proven to be an effective approach to disseminate new and cutting-edge knowledge. Educational institutes in developed countries and professional organizations should be encouraged to extend these opportunities to participants in developing countries. Finally, learned scholars in developed countries should be encouraged to teach others in developing countries, i.e., "train the trainers". This later concept which has proven highly effective in the United States and other countries has great potential for success as a means of outreach to students and work forces in developing countries.
– To accelerate research and education in nanotechnology for agriculture, an increased intensity in investment is critically needed. Government funding agencies, agriculture and allied industries, venture capitals, and other financial institutes should consider investing in nanotechnology R&D for agriculture and foods as the agriculture and renewable production will be centrally important to the global sustainability and will require intensified investment to develop technical capabilities and solutions to effectively address numerous technical challenges ahead.
– International cooperation is germane and essential in an ever increasing globalized economy. Each country has limited resources to invest in research and education. Therefore, working in a complementary manner and combining resources will allow for the effective advancement in nanoscale science and responsible development and deployment for the benefit of society. International organizations such as UN/FAO, WHO, IUFoST, and others should promote and facilitate international exchanges and cooperation. Most recently, the International Union of Food Science and Technology (IUFoST) has approved the formation of International Society of Food Applications of Nanoscale Science

(ISFANS), with its vision "to strengthen research, communication, dissemination of information and networking for technology transfers and international collaborations among interested parties from academia, industry, government, consumers, and other participants around the world. " The formation of ISFANS is but one of many ways to effectively promote and improve international cooperation and collaboration. In addition, governments can also help bilateral and multilateral scientific cooperation through their respective MOUs. Finally, academia has a long history of international collaboration through joint research and training graduate students and postdoctoral fellows which should be encouraged.

Concluding remarks

This paper has intended to provide a brief overview of nanotechnology applications in agriculture in the context of an insight of the current situation around the world, and to form the basis of recommendations and future strategies based on some of current scientific knowledge. Some potential beneficial applications, implications for human and environmental health, challenges (including technical, financial and capacity-related challenges) as well as opportunities and strategies for developing countries have been identified. Finally, possible mechanisms for partnerships and collaborations (e.g., between developed and developing countries, public–private, between research institutions and international organizations etc) are also identified and suggested.

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