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How Will Nanotechnology Affect Agricultural Supply Chains?

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Abstract

The development of nanotechnology creates an excellent opportunity to address complex technical issues of agricultural supply chains and heralds revolutionary changes. The potential application of nanotechnology to the agricultural and food supply chain is reviewed. Although there is evidence that nanotechnology could enhance agricultural supply chains, further research is necessary to determine whether awareness of the technical advances and benefits alone will be sufficient to overcome resistance to the implementation of these new technologies. Failure to embrace nanotechnology will deny the sector an opportunity to capitalize on improved product visibility, food safety, quality and security and associated economic benefits..

Keywords: nanotechnology, agricultural products supply chain, agri-food supply chain, nanosensors, nan composites, supply chain management, smart supply chain.

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Introduction

The next decade offers a period of unprecedented opportunity for newly-developed information and communication technologies (ICTs) to facilitate the rapid transformation of Supply Chain Management (SCM). SCM integrates major business functions and business processes within and across companies into a cohesive and high-performing business model. In addition to logistics management, SCM includes manufacturing operations and coordination of marketing, sales, product design, finance and information technology processes and activities (Nagurney 2006; Wikipedia 2012; CSCMP 2012).

Agricultural supply chains present one of the most significant opportunities for the utilisation of ICT developments to increase the efficiency and effectiveness of SCM. These supply chains have typically focussed on the movement of food from production to consumption. They include all the input supply, production, post-harvest, storage, processing, marketing, distribution, food service and consumption functions in the 'paddock-to-plate' or 'food-to-fork' continuum for a given food product (be it consumed fresh, processed and/or from a food service provider), including the external enabling environment. These functions typically span other supply chains, geographic and political boundaries and often involve a wide range of public- and private-sector institutions and organizations (Jaffee, Siegel, and Andrews 2008; Abatekassa and Peterson 2011; Porter, Baker, and Agrawal 2011).

Agricultural supply chains have unique characteristics which distinguish them from generic supply chains. Firstly, the agricultural chain from production to consumption is highly fragmented. As a result, information about market supply-and-demand and competitors and partners is widely dispersed and difficult to analyse. Secondly, the market price of agricultural production is subject to seasonal variation; and finally, the perishable nature of fresh produce limits the level of adjustment that can be made to accommodate variations across regions and seasons, in particular managing demands for logistics, warehousing, transportation and distribution level activities (Sporleder and Boland 2011).

Nanotechnology is a rapidly evolving technological solution that has enormous potential in agricultural supply chains. However, most of the current focus is on the technology itself, rather than how it could be applied to agricultural supply chains. The benefits from the technology are widespread; it has the potential to improve both products and processes, and in some cases, create new ones. As is to be expected with new technologies, there are also concerns about toxicity, the impact on human and environmental health and loss of privacy.

Nanotechnology is concerned with manufacturing to dimensions or tolerances of 100 nanometres to below 1 nanometre - from the ultraviolet wavelength to atomic dimensions (Franks 1987). Customized manufactured products are made from atoms; their properties depend on how those atoms are arranged. This is in effect the construction of functional systems on a molecular scale. Nanotechnology may be able to create many new materials and devices in a vast range of customized applications, such as medicine (e.g. engineered stem cells, implantable devices, customized antibodies), electronics (e.g. nanochips, nanosensors), materials (e.g. green concrete, smart polymers), food production (e.g. nano-modified, nano-additives) and energy creation (e.g., solar cells, light-trapping photovoltaics).

Alongside genetic technology and information technology, nanotechnology is one of the triad of advancements driving the future transformation of supply chains worldwide (Hewett 2006). Nanotechnology has already been applied to the management of supply chain processes associated with food quality, handling, packaging, and safety. In the field of agricultural supply chains, nanotechnology deployment is already bringing potential benefits to farmers, the food industry and consumers alike, through innovations in agri-food production, processing, preservation and packaging (FAO/WHO 2010).

A number of recent reports and reviews have identified the current and short-term projected applications of nanotechnologies in the agriculture food sector. The main areas of application include food packaging and food products that contain nanosized or nano-encapsulated ingredients and additives. The development of nanosized ingredients and additives appears to be directed towards enhanced uptake and bioavailability of nanosized substances in the body, although other benefits, such as improvement in taste, consistency, stability and texture have also been claimed (Kuzma and VerHage 2006; Bouwmeester et al. 2007; Chaudhry et al. 2007; Chaudhry et al. 2008; Groves 2008; FSAI 2008; Morris 2008; FAO/WHO 2010). For nanotechnology to move beyond its early promise, thereby transforming the management of agri-food supply chains and securing competitive advantage, the communications gap between technology providers and potential users needs to be bridged. Critical to this will be the recognition of the shared role of businesses, universities, research institutes and technology transfer organizations, in determining how nanotechnologies can improve agri-food supply chain management (Wilkinson 2002).

This paper reviews the application of nanotechnology to the agricultural supply chain. Because research into nanotechnology deployment in packaging is already well advanced, this paper will only highlight some examples of previous research before exploring in greater detail areas where research remains emergent. In the first section, issues related to nanotechnology in packaging will be reviewed under four basic types – polymer nanocomposites, antimicrobial, nanosensors and nanocoated films. In the second section we will report on the current application of nanosensor technology in tracking and tracing the supply chain. Following an examination of the potential application of nanotechnology in storage and distribution, the use of nanotechnology to enhance the supply chain safety and efficiency will be discussed. The final section concludes the study and summarises both findings and implications for future research.

Nanotechnology in Packaging

Some of the innovative developments in nanotechnology are likely to transform the food industry by revolutionizing food packaging and safety (Meetoo 2011). Most studies in this area have focused on food safety, examining how it can be used to control microbial growth, delay oxidation, improve tamper visibility, and create more convenience for both suppliers and consumers. Successful implementation would result in longer shelf life, safer packaging, better traceability of food products, and healthier food. This restricted application already supports development of improved tastes, color, flavor, texture and consistency of foodstuffs, increased absorption and bioavailability of nutrients and health supplements, new food packaging materials with improved mechanical, barrier and antimicrobial properties, and nano-sensors for traceability and monitoring the condition of food during transport and storage. Even before consideration of more broad applications, it is predicted that nanotechnology will become one of the most powerful forces for innovation in the food packaging industry (Akbari, Ghomashchi, and Moghadam 2007).

Nanomaterials have multiple applications in food packaging systems, and these can overlap. Some immobilized enzymes, for example, can act as antimicrobial components, oxygen scavengers and/or nanosensors (Azeredo, Mattoso, and McHugh 2011). Accepting that there will be cross-over and blurring at the edges, there are four basic categories of applied nanotechnology research for food packaging: polymer nanocomposites, antimicrobial packaging, intelligent packaging concepts based on nanosensors, and nanocoated films. Of these, the research and application of polymer nanocomposites, antimicrobial packaging and nanocoated films is more advanced and some nano packaging products are already on the market. There is little doubt that intelligent packaging technology based on nanosensors will also have a significant impact on the food and agricultural supply chain. However allowance must be made for the inevitable delay between research outcomes and the development of a functional, commercial application.

Polymer Nanocomposites Packaging

Nanocomposite technology and materials can be used to improve the physical properties of packaging materials, to increase mechanical strength, thermal stability, gas barrier, physicochemical, and recyclability properties (Sorrentino, Gorrasi, and Vittoria 2007; Arora and Padua 2010). As Öchsner, Ahmed, and Ali suggested the properties of nanocomposites depend less upon their individual components than mixing two or more materials which are dissimilar on the nanoscale in order to control and develop new and improved structures and properties (Öchsner, Ahmed, and Ali 2009).

Montmorillonite and kaolinite clays show good potential and novel carbon-based graphene nanoplates are highly promising as nancomposites (Arora and Padua 2010). When incorporated into polymer matrices, nanomaterials interact with the food and/or its surrounding environment, thus providing active or 'smart' properties to packaging systems. Such properties, when present in food packaging systems, are usually related either to improvements in food safety/stability or information about the safety/stability status of a product (Azeredo, Mattoso, and McHugh 2011). Natural biopolymer bio-nanocomposites-based packaging materials have great potential for enhancing food quality, safety, and stability as an innovative packaging and processing technology (Neethirajan and Jayas 2011). Plantic Technologies Ltd, Altona, Australia has manufactured and is selling biodegradable and fully compostable bioplastics packaging (Taylor and Thyer 2006). This is constructed from organic corn starch using nanotechnology (Neethirajan and Jayas 2011). Bio-degradable bio-nanocomposites prepared from natural biopolymers such as starch and protein exhibit advantages as a food packaging material by providing enhanced organoleptic characteristics such as appearance, odour, and flavour (Zhao, Torley, and Halley 2008). The unique advantages of natural biopolymer packaging include their ability to handle particulate foods, act as carriers for functionally active substances, and provide nutritional supplements (Rhim and Ng 2007).

Nanomaterials offer an opportunity to enhance the mechanical and thermal properties of packaging to improve the protection of foods from undesirable mechanical, thermal, chemical, or microbiological effects. For instance, nanoparticles bonded in polymers can enhance material properties such as reducing weight, increasing recyclability, lessening spoilage and loss of and cross-contamination of flavors. Nanocor®, a global supplier of nanoclays, has developed Imperm®. Described as a gas barrier resin, Imperm® is a nanocomposite containing nanoclay particles, which restricts gas permeation, reducing the loss of carbon dioxide and impeding the ingress of oxygen, which, when used in the manufacture of beer bottles, maintains the freshness of the beer, giving it a six-month shelf-life (Asadi and Mousavi. 2006). In addition the bottles are stronger and lighter and less likely to shatter. Similar technology is also being developed for the US Government as a bio-security application which may be capable of detecting possible terrorist attacks on the US food supply (Ravichandran 2010; Nanotechnology 2011; Dingman 2008). Another everyday application is the detection of the molecular changes as milk begins to spoil. These changes could be used to trigger a reaction with nanoparticles embedded in the milk cartons, resulting in the carton changing colour indicating a deterioration in the milk quality. This would provide a visual sign to retailers and consumers about the "freshness" of the milk (Nanotechnology 2011; Dingman 2008).

Kriegel et al (2009) have developed a methodology which uses an electrospinning technique to make biodegradable "green" food packaging from chitin. Chitin is a natural polymer and one of the main components of lobster shells. The electrospinning technique used involves dissolving chitin in a solvent and drawing it through a tiny hole with applied electricity to produce nanoslim fibre spins. These strong and naturally antimicrobial nanofibres have been used for developing the "green" food packaging (Neethirajan and Jayas 2011). Many companies are creating a competitive advantage by producing food packaging bags and sachets from biodegradable polylactic acid and polycaprolactone obtained from the polymer nanocomposites of the corn plant (Bordes, Pollet, and Avérous 2009; Neethirajan and Jayas 2011).

Polymer nanocomposite technology holds the key to future advances in flexible, intelligent, and active packaging. Once production and material costs decrease, companies will be able to use this technology to increase their products' stability and survivability through the supply chain to deliver higher quality to their customers while reducing costs (Mohan 2005). However, further work is required in the development of more compatible filler-polymer systems, better processing technologies, and a systems approach to the design of polymer-plasticizer-fillers (Magnuson, Jonaitis, and Card 2011).

Antimicrobial Packaging

Microorganisms are the most common cause of food poisoning and cause food spoilage, rendering food unfit for human consumption. Antimicrobial packaging systems can extend a product's shelf life and maintain food safety by reducing the growth rate of microorganisms. This is of obvious benefit to the food industry and consumers. Anti-microbial nanoparticle coatings in the matrix of the packaging material can reduce the development of bacteria on or near the food product, inhibiting microbial growth on non-sterilized foods and maintaining the sterility of pasteurized foods by preventing post-production contamination.

Antimicrobial packaging systems include the addition of an antimicrobial nanoparticle sachet to the package, dispersing bioactive agents in the packaging; coating bioactive agents on the surface of the packaging material, and utilizing antimicrobial macromolecules with film-forming properties or edible matrices (Coma 2008). Applications of packaging nanotechnologies have been shown to increase the safety of food by reducing material toxicity, controlling the flow of gases and moisture, and increasing shelf life (Watson, Gergely, and Janus 2011).

There is a broad range of antimicrobial nanoparticles that have been synthesized and tested for applications in antimicrobial packaging and food storage boxes; these include silver oxide nanoparticles (Sondi and Salopek-Sondi 2004), zinc oxide, and magnesium oxide nanoparticles (Jones et al. 2008) and nisin particles produced from the fermentation of bacteria (Gadang et al. 2008).

Foods that are prone to spoiling on the surface, such as cheese, sliced meat, and bakery products, can be protected by contact packaging imbued with antimicrobial nanoparticles. Rodriguez, Nerin, and Batlle (2008) developed an antifungal active-paper packaging, incorporating cinnamon oil with solid wax paraffin using nanotechnology as an active coating; this proved to be an effective packaging material for bakery products. Working with oregano oil and apple puree, Rojas-Grau et al. (2006) created edible food films that are able to kill Escherichia coli bacteria (Neethirajan and Jayas 2011).

CTC Nanotechnology GmbH, Merzig, Germany has manufactured and is now selling a nanoscale dirt-repellent coating to create self-cleaning surfaces for use in food packages and meat-processing plants. This concept is based on a sol-gel process in which nanoparticles are suspended in a fluid medium. By the action of nanohydrophobisation, the absorbency of the surfaces to be treated is eliminated so that they remain resistant to environmental factors after cleaning, with the added advantage that this product is biodegradable and approved and certified for use with food (Neethirajan and Jayas 2011).

Intelligent Packaging Concepts Based on Nanosensors

Nanosensors in intelligent packaging can be designed to indicate the freshness of food, reduce spoilage by releasing preservatives and, based on the consumer's preferences or needs, adjust the sensory appeal and/or nutritional value by secreting colors, flavors or supplements. The use of nanotechnology can, for example, modify the permeation behavior of foils, increase barrier properties (mechanical, thermal, chemical, and microbial), improve mechanical and heat-resistance properties, develop active antimicrobic and antifungal surfaces, and sense as well as signal microbiological and biochemical changes(Tiju and Morrison 2006; Neethirajan and Jayas 2011; Brody 2003; Chaudhry et al. 2008).

One innovative deployment of nanotechnologies in packaging solutions is the reduction of spoilage through deployment of sensors built into food packages (Busch 2008). Nanosensors have been developed which can be applied as labels or coatings to add an intelligent function to food packaging in terms of ensuring the integrity of the package through detection of leaks (for foodstuffs packed under vacuum or inert atmosphere), indications of time–temperature variations (e.g., freeze–thaw–refreezing), and microbial safety (deterioration of foodstuffs)(FAO/WHO 2010; Mahalik and Nambiar 2010; Watson, Gergely, and Janus 2011). Intelligent food packaging can sense when contents are spoiling, and alert the retailer and consumer. Furthermore production, processing, and shipment of food products could be made more secure through the use of nanosensors for pathogen and contaminant detection (Dingman 2008).

Food safety requires confirmation of the provenance and authenticity of a product. Nanobarcodes incorporated into printing inks or coatings show excellent potential for the management of product tracing and the authenticity of the packaged product (Han et al. 2001). Food quality indicators have also been developed to provide visual indications to the consumer of when a packaged foodstuff starts to deteriorate. Used for meat, a nanosilver layer is opaque light brown initially, but if the meat starts to deteriorate, silver sulphide is formed and the layer becomes transparent, indicating that the food may be unsafe to consume (FAO/WHO 2010). In addition, spoilage can be revealed, for example, by an indicator that turns from transparent to blue, informing the consumer that air has entered the modified atmosphere of the packaged materials. For this type of application, nanotechnology-derived printable inks have been developed. An oxygen-detecting ink containing light-sensitive (TiO2) nanoparticles detects only oxygen when 'switched on' with UV light (Park et al. 2007). Other conductive inks for ink jet printing based on copper nanoparticles have also been developed (Park et al. 2007; FAO/WHO 2010).

One of the most promising innovations in smart packaging being pursued by many companies has been the use of nanotechnologies to develop antimicrobial packaging to prolong product shelf-life (Meetoo 2011) and reduce the need for man-made preservatives (Sekhon 2010). One material developed for potential food packaging applications is based on nanostructured silicon with nanopores. The potential application includes detection of pathogens in food and variations of temperature during food storage. Another relevant development is aimed at providing a basis for intelligent preservative packaging technology that will release a preservative only when the packaged food begins to spoil (ETC-Group 2004; FAO/WHO 2010).

The apparent benefits of substituting active ingredients or carriers with nanosized equivalents has also opened the door to research into the potential applications of nanotechnology to pesticides, veterinary medicines and other agrochemicals such as fertilizers and plant-growth regulators. The anticipated benefits, which are driving current R&D in these areas, include a potential reduction in the use of certain agrochemicals (such as pesticides) and an increased ability to control the application and dosage of active ingredients in the field. Despite a great deal of industrial interest in this area, research is still in an embryonic stage. Although most developments are currently at a developmental stage, it is likely that the agriculture sector will see some large-scale applications of nanotechnologies in the next decade that will alert the consumer to the agrochemicals currently being used in the agriculture production (MacKenzie 2007; FAO/WHO 2010).

There are many other research initiatives exploring more complex, smarter packaging. These include the use of an array of nanosensors which are sensitive to gases released by food as it spoils, indicating if it is no longer 'fresh' (Meetoo, 2011) or triggering the release of preservatives to extend the life of the food (Ravichandran 2010). Kraft Foods is also engaged in producing products which incorporate nanosensors that detect a consumer's food profile of likes and dislikes, allergies and the person's nutritional deficiencies. Nanotechnologies could then respond by releasing accurately controlled amounts of suitable molecules to tailor the smell, taste and nutritional value of the product to match the personal preferences of an individual consumer (Meetoo 2011)..

Nanocoated Films

Nanofilms have the virtue of keeping unwanted materials or contaminants out of food, as well as improving the protection of food sealed inside the package. Nanocoated films are usually composed of layers of polymers that are designed as barriers to flavour, water, and/or gas. Studies have shown that layers of nanoparticles imbedded within a single polymeric film (nanocomposites) improve upon a previous layer polymeric film's barrier and protection properties (Kuzma, Romanchek, and Kokotovich 2008; Meetoo 2011).

A wide number of nanoparticles, including silica, silicate, clay, organomontmorillonite, and calcium carbonate, are used in nanocomposites for food packaging (Chu, Keung, and Su 2003; Lagaron et al. 2005; Kuzma, Romanchek, and Kokotovich 2008). These particles fall under the more general category of clay nanoparticles, or 'nanoclays'. Clays exist in a structure held together in crystalline form. By breaking the crystal structure leaving only the platelets, a nanoclay is created (Frazer 2004). The high aspect ratio (width divided by height) and the large surface area create desirable barrier properties, reinforcing efficiency, and improving thermal stability (Zeng et al. 2003). The nanoclays are then imbedded into a polymer film to create a nanocomposite. These nanocomposites decrease the diffusion of oxygen and carbon dioxide in and out of packaging material, keeping food fresher for longer periods of time. They also help reduce the health risks associated with bacterial growth in food i.e., lower oxygen for growth (Kuzma, Romanchek, and Kokotovich 2008).

Many recent developments are extending even further the potential for nanocoated films to enhance the safety and quality of food supply (Magnuson, Jonaitis, and Card 2011). The foundations of the current research can be found in a study by De Moura et al. (2008), that showed how the tensile, water vapour, and oxygen-permeable properties of edible films could be significantly improved through the application of nanoscience. Azeredo et al. (2010) described the use of cellulose nanofibers and glycerol as a plasticizer to improve the mechanical and water-vapour barrier properties of edible chitosan films. They reported that nanocomposite film with 15% of cellulose nanofibers and plasticized with 18% glycerol was not only comparable in strength and stiffness to some synthetic polymers, albeit with poorer elongation and water vapour barrier properties, but was also extremely environmentally friendly. In 2011, Dobon et al. (2011) outlined the potential cost savings from deployment of a new smart-packaging concept with a communication capability embedded in a device. This allows the expiry date of the product to change as a function of temperature during transport and storage; in effect a flexible best-before-date (FBBD).

Nanotechnology in Tracking and Tracing

Nanotechnology can enhance agricultural SCM by improving supply chain visibility, food authenticity, tracking and traceability and ultimately food security through features that assist avoid counterfeiting, product adulteration and diversion (Neethirajan and Jayas 2011; FAO/WHO 2010). Radio Frequency Identification (RFID) technology is widely deployed and globally appreciated as a major technological enhancement to the management of tracking, information collection and reporting within a supply chain. However, the advantage of enhancing RFID with nanotechnology is still emerging. Through experimentation and analysis of results using multiple variables, Mapa, Aryal et al. (2010) confirmed the improved readability of RFID tags in the presence of various nanofluids at different concentrations on a conveyor belt, an example of a typical packaging environment.

Watson Gergely and Janus (2011) concluded that refinements to the use of RFID tags with nanotechnologies used on agricultural products gave government and industry greater supply chain and product traceability in the event of a food recall. RFID tags or 'smart' labels are being developed with displays that enable rapid and accurate distribution of a wide range of products (including foodstuffs) that have a limited shelf-life. RFIDs incorporating polymeric transistors that use nanoscale organic thin-film technology are under development. The smart tag system will be designed to operate automatically providing exception reports for anomalies in temperature and other factors that affect the quality and safety of perishable foods products and products with a short life span (Garland 2004).

To help in the tracking and tracing, nanotechnology provides complex invisible nanobarcodes with batch information which can be encrypted directly onto the food products and packaging. This nanobarcode technology offers food safety by allowing the brand owners to monitor their supply chains without having to share company information with distributors and wholesalers (Neethirajan and Jayas 2011). It is interesting that nanotechnology can provide not just security but also the enforcement of brand-protection. Nanotechnologies can be embedded in a product to enable brand owners to assure customers of its authenticity and for investigators to identify genuine goods, making it very difficult for counterfeiters to imitate. Using nanotechnology, companies can encrypt unique product information such as data about growing conditions — climate and soil — collected from on-farm sensors. This can not only inform buyers about food quality, but also confirm product pricing and, very importantly, assure greater security and safety if a product recall requires data relating to product origins. Nanotechnology can also be encrypted with logistics information, such as processing or batch information, directly onto the product or packaging (Roberts 2007). Oxonica in the United Kingdom offers solutions for food product identification and brand authenticity whereby the nanobarcodes become a biological fingerprint created by nanoparticles which generate unique reading strips for every food item (Neethirajan and Jayas 2011).

In order to allow better information delivery in tracking and tracing, some nano-based products may be able to encrypt information technology in the form of nanodisks functionalized with dye molecules to emit a unique light spectrum when illuminated with a laser beam, so that they can be used as tags for tracking food products (Nam, Thaxton, and Mirkin 2003). A nanobarcode detection system is being developed that fluoresces under ultraviolet light in a combination of colours that can be read by a computer scanner (Li, Cu, and Luo 2005). Dip Pen Nanolithography involves using a scanning probe with a molecule-coated tip to deposit a chemically engineered ink material to create nanolithographic patterns on the food surface (Zhang et al. 2009).

Roehrig and Spieker (2008) present a technique to monitor the manual transportation processes of goods in a warehouse, in order to update the database automatically. In the proposed scenario, transport vehicles such as forklift trucks or pallet jacks would be equipped with wireless sensor nodes and every storage and retrieval activity would be reported to the warehouse management system. Tracking of transport vehicles is performed with nanoLOC sensor nodes, which offer range measurement capabilities. This radio positioning system determines the range between two devices by measuring the signal propagation delay. The tracking of transport vehicles with range measurements and trilateration could be carried out by using the Extended Kalman Filter. Experimental results were presented of tracking a forklift truck in a warehouse.

Due to the cost of introduction and user acceptance of such applications, nanotechnology in tracking and tracing within agricultural supply chains is still in the experimental stage, although there is a considerable amount of research being undertaken. It should be noted that there are some applications of nanotechnology already introduced into industry supply chains; early success of such applications suggests they could be introduced into the supply chain of agricultural products with positive effect.

Nanotechnology in Storage and Distribution

The quality of goods in storage and distribution can be adversely affected by changes in the storage environment, such as temperature, humidity and odour. Nanotechnology can be applied to agri-food SCM track and report these changes.

Packaging that incorporates nanomaterials can respond to environmental conditions to self - repair or alert the consumer to contamination and/or the presence of pathogens (Baeumner 2004). Such packaging enhances information collection and product management in relation to environmental conditions relating to such factors as temperature and moisture during storage and distribution. In providing solutions for these problems, nanotechnologies can modify the permeation behaviour of foils, increasing barrier properties; for example, mechanical, thermal, chemical and microbial, improving mechanical and heat-resistance properties, developing active anti-microbic and anti-fungal surfaces and sensing as well as signalling microbiological and biochemical changes (Meetoo 2011).

Active packaging films for selective control of oxygen transmission and aroma affecting enzymes have been developed based on the nanotechnology approach. Modification of the surface of nanosized materials by dispersing agents can act as substrates for oxidoreductase enzymes (Neethirajan and Jayas 2011). Nanocomposite film can be enriched with an enormous number of silicate nanoparticles that reduce the entry of oxygen and other gases and the exit of moisture, thus preventing food from spoiling (Scheffler et al. 2010). Nanocrystals have been developed that can be used in nanocomposite plastic bottles. This material minimizes the loss of carbon dioxide and the entry of oxygen into beer bottles (Sekhon 2010). Smart-sensor technology could be very useful for monitoring the quality of grain, dairy products, fruit and vegetables in a storage environment in order to detect the source and the type of spoilage (EduTransfer Design Associates 2007).

Liu et al (2011) report that a water quality monitoring sensor composed of single-walled carbon nanotubes has been developed. It can be integrated inside microfluidic channels and on-chip testing components with a wireless transmission board. This nanosensor should be useful for sensing and reporting real time information regarding the product from production through to delivery to the consumer.

Nanotechnology also has shown remarkable properties applicable to other aspects of storage and agri-food distribution. For example:

- Nanoencapsulation offers numerous benefits including ease of handling, enhanced stability, protection against oxidation, retention of volatile ingredients, taste masking, moisture-triggered controlled release, pH-triggered controlled release, consecutive distribution of multiple active ingredients, changes in flavour, long lasting organoleptic perception, and enhanced bioavailability and efficacy (Shefer 2012).

- Nanomaterials with food and bioprocessing applications can be produced from engineered plants or microbes from waste materials such as stalks and other cellulosic materials (Robinson and Morrison 2009).

- Single-walled carbon nanotubes form a nanosensor which, in addition to use in water quality monitoring and fresh fish storage and distribution, can be integrated inside microfluidic channels and on-chip testing components with a wireless transmission board (Liu et al. 2011).

Other Applications in Agri-SCM

Nanotechnology in Supply Chain Safety

Quality assurance in the food supply chain is of the utmost significance, not just because of the legal implications for the producer and supplier, but also because of the importance of satisfying increased demand from consumers for safe and quality food and to meet stringent government food safety regulations. Nanotechnology has shown significant promise in the enhancement of sensors able to detect spoilage or changes to product quality. To ensure food safety, EU researchers in the Good Food Project have developed a portable nanosensor to detect chemicals, pathogens and toxins in food (Tiju and Morrison 2006). This circumvents the very time consuming and expensive alternative of sending samples to laboratories. Food can be analysed for safety and quality at control points in the supply chain; for instance at the farm, abattoir, during shipping, at the warehouse or storage depot, and at the processing or packaging plant. They are also developing a device which uses DNA biochips to detect pathogens - a technique that can also be applied to determine the presence of different kinds of harmful bacteria in meat or fish, or fungi affecting fruit. In addition there are plans to develop microarray sensors that can be used to identify pesticides in fruit and vegetables as well as those which will monitor environmental conditions at the farm. These have been called 'Good Food Sensors' (Tiju and Morrison 2006).

Nanosensors are far from being just a passive, information-receiving device. They can receive information from immediate and remote contexts and can analyse, record and report data. They can be designed to do this at critical control points in the supply chain over the period of time from the point food is produced or packaged, through to the time it is consumed. The latest developments have resulted in nanosensors able to provide quality assurance by tracking microbes, toxins and contaminants through the food processing chain by using data capture for automatic control functions and documentation.

Advances in miniaturized instrumentation have also resulted in the development of biosensors capable of integrating bio-recognition and spectroscopy tools to support pathogen detection, thus addressing safety concerns in the food supply chain. The development of smart and robust sample preparation methods can lead to the effective incorporation of similar strategies over a wide array of currently available mid-IR technologies that can be used in field at sites-of contamination as portable sensors (Ravindranath 2009). In another development, a direct-charge transfer (DCT) biosensor has been created that uses antibodies as sensing elements and polyaniline nanowire as a molecular electrical transducer (Pal, Alocilja, and Downes 2007). The resulting biosensor could be used for the detection of the foodborne pathogen, Bacillus cereus**.**

Nanotechnology in Supply Chain Efficiency

Smart sensors, that is sensors which have "intelligence" capabilities are likely to revolutionise agriculture supply chain management in the near future (5-8 years). Smart sensing is mostly applicable to micro-electromechanical systems (MEMS) technology, which integrates mechanical elements, sensor material and electronics on a common silicon chip through microfabrication techniques. Initial work by the Intermec Technologies Corp. to use MEMS-based technology in supply-chain data collection equipment has confirmed it is possible to produce laser data collection scanners that are significantly faster, smaller, lighter and more efficient than today's legacy scanners (Anon 2005). Subsequent tests confirm that MEMS-based laser scanners are able to read bar codes up to 40 times faster with more accuracy; a massive advancement over existing scanner technologies that highlights the need for even better information management technologies to be developed before improvements to supply chain visibility can be fully realised (Anon 2005). Later developments have therefore moved into a field related to smart sensing - smart decision analytics. This is based on a the capture, analysis and reporting of the data obtained from the smart sensors (Tien 2011). Due to the superiority of nanotechnology, it will soon be possible to embed the present technology in the SCM to improve the efficiency of the supply chain.

Discussion and Conclusions

Agricultural and food supply chain management is complex due to the diverse characteristics of agricultural products. There are numerous types of agricultural products, many of which are perishable. In addition, the degree of standardization of some kinds of agricultural products and their management is still low. Furthermore, agricultural production sites are still very fragmented and often highly dispersed. Because of the inherent complexity of agricultural products, the deployment of technology in the agricultural supply chain has the potential to provide more significant and far-reaching benefits compared to other industries. For example, the tracking and tracing of perishable food products in the supply chain can be more precise than in a manufacturing supply chain. New technology once deployed in the agricultural and food supply chain can be targeted to known problems in order to profoundly improve visibility, promote ubiquitous access to data, promote even higher efficiency and lower costs (Ward, Woods, and Wysocki 2011; Amanor-Boadu, Marletta, and Biere 2009).

As one of the fastest growing areas of research and technology, which is being heralded as the basis of the next industrial revolution (Marchant 2009), nanotechnology offers the potential to make most products lighter, stronger, cleaner, less expensive and more precise. Nanotechnology has the potential to fundamentally alter the way people live, by providing new drug delivery systems, faster and cheaper manufacturing processes, cleaner and more efficient energy generation, new materials, clean water and the next generation of computing devices. In fact, nanotechnology is already having a profound impact on major industries worldwide, including electronics, computers, communications, national defense, energy, biomedical, transport and manufacturing. Nanotechnologies such as nanosensors are sufficiently robust and developed to a point where they can radically reshape supply chains across all locations and types of industries, modes of transport or goods. However, although nanotechnologies can have significant potential to remove complexity and manage variables in the agri-food supply chains, they have not yet been adopted on a large scale.

Nano and nano-intelligent technologies have a wide application to the process of supply chain (e.g. sensors, buy and sell intelligent agents or quality, security and safety control through nano materials in and on food, goods, packaging and freight). For instance nano-sensors can be used in the determination of the ripeness and freshness of packaged produce, and in the detection of pathogens in animal food production systems (e.g. detection of harmful viruses which infect cattle) and in farm, food and environmental samples before they can contaminate the food.

Investigation confirms that incremental application of nanotechnology in the agricultural supply chain, first in the food packaging, and later in other areas such as tracking and tracing and storage and distribution, is occurring. Currently, most nanotechnology applications in the agricultural supply chain are concentrated in packaging, mainly in the improvement of packaging materials for product security, quality and safety. From the point of view of the supply chain, the logical extension is the application of intelligent packaging based on nanosensors with a view to promoting information and management across all elements of an agricultural supply chain. Compared with traditional sensors and their shortcomings, nanosensors have several advantageous properties, such as high sensitivity and selectivity, near real-time detection, and low cost and portability.

Existing nanotechnologies can radically reshape supply chains across all locations and types of industries, modes of transport or goods. The benefits for the agricultural supply chain are equally exciting. Beyond the next phase of development - extending nanotechnology from packaging to nanosensors - there seems to be every reason to examine nanotechnology deployed not as a product specific packaging enhancement, but as an intentional and controlled exercise intent in constructing a 'Smart Supply Chain', in which nanotechnologies are deployed to deliberately improve the level of product visibility, security, quality, safety and introduce efficiencies across an entire agricultural supply chain. Nanotechnologies permit such deployment because they are autonomous, permit a two-way data flow, can be oriented towards human goals and can permit communities of people to work together in more powerful ways than previously conceived of. They remove unnecessary complexity in variables such as diversity of products, locations and characteristics of each product type that have been impeding the positive transformation of the management of agri-food supply chains. Smart Supply Chains in agriculture, as foreshadowed by this review, can leverage existing advancements in nanotechnologies in order to enable supply chain efficiencies only possible through ensuring that product-level data collection is more detailed, more accurate and available almost in real time.

From this review, we can see that nanotechnology has potential applications in every aspect of the agricultural and food supply chain, although some of the specific applications are still slowly transitioning from research into wide-scale, commercial deployment. Given nanotechnologies have been developed to a point where their significant contribution to competitive advantage in agriculture supply chains is known, the gap between technology R&D and adoption by potential businesses remains stark. Despite the overwhelming possibilities demonstrated by scientific research, levels of adoption of the technology within the agricultural supply chain remain relatively low. Furthermore the application of nanotechnologies to agricultural supply chains raises concerns about serious ethical arguments, regulatory and broader human and environmental health issues (European Food Safety Authority 2012; EFSA Scientific Committee 2011; Scientific Opinion of the Scientific Committee 2009).

The economics of nanotechnology application in the agricultural supply chain is no different to the application of other new technologies. Initially, the outlay is relatively high, which impedes uptake of the new technology. Although the cost of some nano packaging materials has been reduced, the price of nano-sensors is relatively high. In the short to medium term, with large-scale applications, as well as the improvement of production technology, nano-technology costs will decrease significantly. In the long term, with the popularity of nanotechnology, the cost of the application of nanotechnology in the agricultural supply chain will become cost effective.

Just as early ICT brought a technological revolution to food and agribusiness industry, nanotechnology will bring revolutionary improvements to the agricultural supply chain. It is imperative that the food and agribusiness industry is aware of and understands the opportunities and challenges that nanotechnology offers. Future technological and managerial innovations should take full advantage of nanotechnology, thus improving the efficiency, food safety, compliance, eco-friendliness, and competitiveness of and realizing the economic benefits for individual producers, companies and the sector in the long term.

Although a large amount of information is now available about the advantages of nanotechnology for agricultural supply chains, further research is needed to realize fully the potential of nanotechnology within the industry. Can the resistance of elements within agricultural supply chains be overcome by simply the knowledge of nanotechnological advances and benefits? Is this knowledge sufficient in itself to accelerate the adoption of these technologies by industry, and lead to improved product visibility and food safety, quality and security? The answers to these questions are of critical importance, not just for those seeking to develop the nano-technology but also for those employing the technologies.

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