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Improving the food safety in supply chain: the value of nanotechnology on a growing problem

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REVIEW ARTICLE

Abstract

Food safety requires more sophisticated and intelligent technology in the food supply chain management. The emergence and development of nanotechnology brings a good opportunity to improve the complex technical issues that food supply chain safety needed and may bring revolutionary changes to the food supply chain in the future. This paper reviews the current and potential application of nanotechnology to every aspect of food safety in supply chains, include the quality detection, packaging, storage and distribution, tracking and tracing. This review suggests that even with communication as to how nanotechnology may advantage food supply chain safety the next area of research must be to investigate if awareness of the technical advances and benefits alone will be sufficient to accelerate adoption of these technologies by businesses to improve product visibility and food safety, quality and security.

Keywords: food safety, food supply chain, nanosensor, nanotechnology, supply chain safety

1. Introduction

Food supply chains have typically focussed on the movement of food products from production to market. They include all the input supply, production, post-harvest, storage, processing, marketing and 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 organisations (Abatekassa and Peterson, 2011; Jaffee *et al.*, 2008; Porter *et al.*, 2011).

Safety assurance in the food supply chain is of the utmost importance 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 the imposition by governments of stringent regulations to ensure food safety. However, food safety has become a popular issue among people which induce more attention to it when more and more food safety accidents happened and brought out more damage to people. Food safety issue in the supply chain is also of concern. Sensors or detection systems for rapid detection of spoilage of product components, for quality control, and for abuse detection at the source and during the supply chain are possible through nanotechnology monitoring (Neethirajan and Jayas, 2011).

Nanotechnology is a rapidly emerging technology that could potentially make most products lighter, stronger, cleaner, less expensive and more precise. Its use raises many of the same issues as with any form of new technology, including concerns about toxicity, environmental impact, and potential socio-economic benefits. Nanotechnology and nanoscale materials constitute a new and exciting field of research (Yonzon *et al.*, 2005). An emerging area of biosensors is based on the use of structures provided by recent advances in nanotechnology, such as nanowires, nanotubes, and nanopores. Among them, the integration of natural nanopores, such as ion channels, with electronics is a promising approach to developing rapid, sensitive, and reliable biosensors (Crescentini *et al.*, 2009).

Nanotechnology holds great promise for the food safety in supply chain management business. For example, nanosensors can be attached to crates, roll containers, pallets, and shipping containers to function as so-called 'active transport tracking devices'. These devices can actively monitor the transportation process and verify the proper handling conditions of goods, like temperature for fresh foods. Furthermore, these devices can detect damage due to sudden shocks, the opening of containers, and other forms of contract breach (Evers *et al.*, 2007). However, the potential of nanosensors can be anticipated to extend beyond such devices. As nanotechnologies are embedded into packaging and even the product (e.g. placed into a pill), the potential able to be realised in the next decade increases exponentially (Bowles and Lu, in press).

A number of recent reports and reviews have identified the current and short-term projected applications of nanotechnologies in the food safety. The main areas of application include food packaging and food products that contain nanosized or nano-encapsulated ingredients and additives. For nanotechnology to move beyond its early promise to make breakthroughs that will transform how food supply chains safety are managed and competitive advantage secured, the communications gap between technology providers and potential users needs to be bridged. This will critically revolve around businesses, universities, research institutes and technology transfer organisations, recognising their shared role in how nanotechnologies can improve food safety in supply chain management (Wilkinson, 2002).

This paper will review the application of nanotechnology to the food supply chain. To complete the review, this paper is organised as follows. In the second section, brief introduction of nanotechnology and its application in and food safety management in supply chain will be reviewed. In the third section we will report on the currently application of nanotechnology in food quality monitor. In Section 4, issues related to nanotechnology in packaging will be reviewed. The potential application of nanotechnology in food storage and distribution is then examined before we move in Section 6 to a discussion of how nanotechnology can be used to enhance the tracking and tracing the food supply chain. In the Section 7, the potential risks of nanotechnology in food supply chain will be discussed. The final section concludes the study and summarises both findings and implications for future research.

2. Nanotechnology and food safety management in supply chain

Nanotechnology is concerned with manufacturing to dimensions or tolerances from 100 nanometers down to below 1 nanometre – from the ultraviolet wavelength to atomic dimensions (Franks, 1987). At this scale, novel nanomaterials and nanoparticles show new properties and behaviours that cannot be observed at the microscopic level. The aim of nanotechnology is to create nanodevices with new functionalities stemming from these unique characteristics; Customised manufactured products are made from atoms and their properties depend on how those atoms are arranged. Nanotechnology may be able to create many new materials and devices in a vast range of customised – and mass customised – applications, such as medicine (e.g. engineered stem cells, implantable devices, customised 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).

Nanotechnology has already been applied in a manner that affects the management of supply chain processes associated with food quality, handling, packaging, and safety. In the field of food supply chains, nanotechnology deployment is already bringing potential benefits to farmers, the food industry and consumers alike, through innovations in food production, processing, preservation and packaging (FAO/WHO, 2010).

Nanotechnology is not solely about developing miniaturised versions of classical machines. One of the early applications of nanotechnology was in the field of nanosensors (Akyildiz, and Jornet, 2010; Hierold *et al.*, 2007; Li *et al.*, 2008a; Riu *et al.*, 2006; Yonzon *et al.*, 2005).

Nanosensors are nanotechnology-enabled sensors characterised by one of the following attributes: either the size of the sensor or its sensitivity is on the nanoscale or the spatial interaction distance between the sensor and the object is in nanometres (Khanna, 2009). Any device conforming to one of these properties will be designated as a nanosensor. For example, a definition of an optical nanosensor is: a device that converts a chemical or biological event using an optical signal, having all dimensions <103 nm (Khanna, 2009). Since the epoch-making inventions of the scanning tunnelling microscope in 1981 and the atomic force microscope in 1986, nanodevices and nanosensors have enjoyed close scientific and public attention (Bogue, 2008; Khanna, 2008). For convenience of study, the nanosensors will be systematically classified into physical (mechanical and acoustical, thermal and radiation, optical, magnetic) and chemical (atomic and molecular energies) categories. The biological domain overlaps both the physical and the chemical sensor domains, and will be covered under these headings as an inter-mixed or interdisciplinary area (Khanna, 2009).

Nanosensors work with their special sensation ability, which can detect information and data. Their arrangement is like ordinary sensors but the major difference between sensors and nanosensors is that nanosensors are developed on the nanoscale, which distinguishes them from ordinary ones. Nanosensors can accurately identify specific cells or parts of the body with any deficiency. They work by calculating and measuring the ups, downs, and changes, displacement, dislocations, concentration, volume, acceleration, external forces' pressure or temperature of each cell in the living body. Many nanosensors are designed to differentiate between normal and abnormal cells, such as sensors for detecting cancer in the living body and molecular controllers to deliver medicines in the human body. They are also able to detect macroscopic changes that appear from external interactions and communicate these variations to the other nanocomponents working alongside them.

Food supply chains have unique characteristics which distinguish them from generic supply chains. Firstly, the food chain from production to consumption is highly fragmented. As a result, market supply and demand information, with regard to competitors and partners is scattered and difficult to fully grasp. Secondly, seasonal agri-food production generates market price fluctuations for agri-food products; and finally, the perishable nature of fresh food products limits instant adjustment to accommodate variations across regions and seasons, especially with regard to managing higher demands for safety management in logistics, warehousing, transportation and distribution level activities (Sporleder and Boland, 2011).

Nanotechnology has significant promise for enhancing the role of sensors able to detect spoilage or changes to food quality. Nanosensors are far from being just a passive, information receiving device. They can receive information from immediate and remote contexts. They 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. Nanosensors can provide quality assurance by tracking microbes, toxins, and contaminants throughout the food processing chain through data capture for automatic control functions and documentation. Nanotechnology also enables the implementation of low-cost nanosensors in food packaging to monitor the quality of food during various stages of the logistic process to guarantee product quality up until consumption (Neethirajan and Jayas, 2011).

3. Food quality monitoring

Potential applications of engineered nanomaterials in food safety during supply chain include (1) monitoring of food quality and biosecurity (for example, via nanosensors); (2) improved food packaging and enhancement of package biodegradability; and (3) improved food processing (Baeumner, 2004; Chen *et al.*, 2006; Sozer and Kokini, 2009). Examples include (1) nanosensors for the detection of foodborne pathogens and contaminants; (2) adhesion-specific nanoparticles for selective binding and removal of pathogens and contaminants (the non-antibiotic approach to disease prevention); (3) active antimicrobials such as metal oxides; and (4) tracers that could help determine sources of contamination (Park *et al.*, 2007; Scott and Chen, 2003). These nanosensors have several advantageous properties, such as high sensitivity and selectivity, near real-time detection, low cost, and portability. Currently, scientists are using nanotechnology to develop rapid and accurate diagnostics and detection methods for pathogens, such as *Staphylococcus aureus*, *Escherichia coli*, *Listeria* monocytogenes, *Campylobacter jejuni*, and *Salmonella*. The opportunities for advancement and benefits in this area are great, but still require a significant amount of research (Magnuson *et al.*, 2011).

Grain quality monitoring nanosensors, which are being developed by researchers at the Canadian Wheat Board Centre for Grain Storage Research, University of Manitoba, Canada, use conducting polymer nanoparticles (Neethirajan and Jayas, 2011), which respond to analytes and volatiles in food storage environments and thereby detect the source and the type of spoilage. The advantage of this sensor system is that thousands of nanoparticles can be placed on a single sensor to detect accurately the presence of insects or fungus inside stored grain bulk in bins. Because of the miniaturisation and low power requirement, the nanosensors can be fabricated small and lightweight (Neethirajan and Jayas, 2007) and can be deployed and distributed into the crevices of grain bulk, where the stored product pests often hide.

The advancements in miniaturised instrumentation have accelerated the development of biosensors capable of integrating biorecognition and spectroscopy tools with specifications capable of supporting pathogen detection to address safety concerns in the food supply chain. The ideal method for pathogen detection would require minimal sample preparation, rapid and automated analysis, and non-invasive and quantitative inexpensive assessment. The development of smart and robust sample preparation methods can lead to effective incorporation of similar strategies over a wide array of currently available Mid-IR technologies that can be used in the field as portable sensors at sites of contamination (Putta Ravindranath, 2009).

Alocilja *et al.* (2007) developed a direct-charge transfer biosensor for the detection of the foodborne pathogen, *Bacillus cereus*. The biosensor was fabricated using antibodies as the sensing element and polyaniline nanowire as the molecular electrical transducer. The sensor design consisted of four membrane pads, namely sample application, conjugate, capture, and absorption pads. Two sets of polyclonal antibodies, secondary antibodies conjugated with polyaniline nanowires, and capture antibodies were applied to the conjugate and the capture pads of the biosensor, respectively.

Ruengruglikit *et al.* (2004) have developed an electronic tongue for inclusion in food packaging that consists of an array of nanosensors that are extremely sensitive to gases released by food as it spoils, causing the sensor strip to change colour as a result, giving a clearly visible signal of whether the food is fresh or not.

Electronic instruments mimicking the mammalian olfactory system are often referred to as 'electronic noses' (e-noses). Nanotechnology breakthroughs in the fabrication mean that mesoscopic and even nanoscopic e-noses are now feasible in the size domain where miniaturisation of the microanalytical systems encounters principal limitations (Sysoev *et al.*, 2010).

4. Food packaging and nanotechnology

Research into nanotechnology deployment in food packaging and safety solutions has tended to focus more on food safety, by examining how it can be used to control microbial growth, delay oxidation, improve tamper visibility, and create more convenience. However, this deployment alone has wide ranging benefits. Applications in food already support development of improved tastes, colour, flavour, 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 (Lu and Bowles, 2013). Because research into nanotechnology deployment in packaging is already well advanced, this paper only briefly revisit some examples of previous research before delving deeper into areas where less research has occurred.

Nanocomposite technology and materials can improve their physical properties in order to make possible increased utilisation of food packaging biopolymers, such as mechanical strength, thermal stability, gas barrier, physico-chemical, and recyclability (Arora and Padua, 2010; Sorrentino *et al.*, 2007). When incorporated into polymer matrices, nanomaterials may 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 *et al.*, 2011).

Antimicrobial packaging systems can extend a product's shelf life and maintain food safety by reducing the growth rate of microorganisms. They are important for 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-sterilised foods and maintaining the sterility of pasteurised foods by preventing post-contamination.

Antimicrobial packaging systems include procedures such as (1) adding an antimicrobial nanoparticle sachet to the package; (2) dispersing bioactive agents in the packaging; (3) coating bioactive agents on the surface of the packaging material; or (4) utilizing antimicrobial macromolecules with film forming properties or edible matrices (Coma, 2008). Applications of packaging nanotechnologies have increased the safety of food by reducing material toxicity, controlling the flow of gases and moisture, and increasing shelf life (Watson *et al.*, 2011).

Nanotechnology has enabled the development of nanosensors that 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), or microbial safety (deterioration of foodstuffs) (FAO/WHO, 2010; Mahalik and Nambiar, 2010; Watson *et al.*, 2011). Production, processing, and shipment of food products could be made more secure through the use of nanosensors for pathogen and contaminant detection (Dingman, 2008).

Intelligent food packaging can sense when its contents are spoiling, and alert the consumer, while active packaging will release a preservative such as antimicrobials, and flavours, colours, or nutritional supplements into the food when it begins to spoil. Nanotechnology can provide solutions for these, for example modifying the permeation behaviour of foils, increasing barrier properties (mechanical, thermal, chemical, and microbial), improving mechanical and heat-resistance properties, developing active antimicrobic and antifungal surfaces, and sensing as well as signalling microbiological and biochemical changes (Brody, 2003; Chaudhry *et al.* 2008; Joseph and Morrison, 2006; Neethirajan and Jayas, 2011). Examples include 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. One example is an oxygen detecting ink containing light-sensitive (TiO_2) nanoparticles which only detect oxygen when they are 'switched on' with UV light (Bong Kyun *et al.*, 2007). Other conductive inks for ink jet printing based on copper nanoparticles have also been developed (Bong Kyun *et al.*, 2007; FAO/WHO, 2010).

A wide number of nanoparticles, including silica, silicate, clay, organomontmorillonite, and calcium carbonate, are used in nanocomposites for food packaging (Chu *et al.*, 2003; Kuzma *et al.*, 2008; Lagaron *et al.*, 2005). 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 *et al.*, 2008).

5. Nanotechnology in food storage and distribution

Nanotechnology can be applied to food safety in supply chain management in storage and distribution, mainly for the detection of environmental and quality changes in storage and distribution processes (Lu and Bowles, 2013). In such processes, the changes in the environment that food products experience such as temperature, humidity or odour that may lead to the deterioration of the quality of food products when they are being transported need to be tracked and reported.

Hazardous gas and vapour detection

Oxygen inside food packaging is the main cause of food deterioration due to the oxidation of fats and oils and the growth of microorganisms. Also, oxygen accelerates the processes inside food packaging, leading to discolouration, changes in texture, rancidity and off-odour, and flavour problems. Nanotechnology can effectively produce (1) oxygen scavengers for sliced processed meat, beer, beverages, cooked pastas, and ready-to-eat snacks; (2) moisture absorber sheets for fresh meat, poultry, and fish; and (3) ethylene-scavenging bags for the packaging of fruit and vegetables.

A number of novel developments are occurring that all hold relevance to nanosensors' ability to detect breakdowns in packaging or storage environments. Nanostructure-engineered chemical sensors used to detect hazardous gas and vapour detection and applications (Li and Lu, 2004) could also be applied to nanosensors used to detect gas and vapour in storage containers or environments. Liu *et al.* (2011) confirmed that single-walled carbon nanotubes, with their unique electrical properties and large surface area, are remarkable materials for detecting low concentrations of toxic and hazardous chemicals (from both the gaseous and the liquid phase).

Aroutiounian *et al.* (2008a) presented nanosensors based on ultrathin SnO(2) films, which are very sensitive to the highly toxic gases SO(2) and H(2)S. The sensor resistance is decreased in the presence of the toxic gases (Aroutiounian *et al.*, 2008a). Gouma *et al.* (2011) proposed a three-nanosensor array microsystem that may potentially serve as a coarse diagnostic handheld breath analyser to provide a first detection device. Newaz *et al.* (2010) reported an individually addressable Ti/GaAs metal-semiconductor hybrid optical nanosensor with positive photoresistance and sensitivity that increases as the device dimensions shrink for room temperature light detection. Liu *et al.* (2011) reported a water quality monitoring sensor composed of single-walled carbon nanotubes integrated inside microfluidic channels and on-chip testing components with a wireless transmission board. This type of nanosensor would be useful for water quality monitoring for fresh fish storage or water transportation units.

Storage temperature

Iliadis and Ali (2011) reported a highly responsive gas nanosensor operating at room temperature. The nanosensor is formed by self-assembly of ZnO nanoparticles in a polyacrylic matrix spin-cast on p-type (100) Si at room temperature, in complementary metal oxide semiconductor compatible processing. Sensitivity was consistently higher for the small nanoparticles, especially for lower gas concentrations. Lee *et al.* (2011) demonstrated a novel sensing system comprised of amino acid mediated grown gold nanoparticle chains, which shows a sub-ppm lower detection limit toward H_2S with rapid response and recovery times at room temperature. This sensing system can be used for storage temperature detection.

Aroutiounian *et al.* (2008b) realised a porous silicon near-room-temperature nanosensor covered by thin TiO(2) or ZnO films. This nanosensor is possible to realise a hydrogen nanosensor with relatively high sensitivity and selectivity to hydrogen, durability, and short recovery and response times. Such a sensor can also be part of a silicon integral circuit and work at near-room temperature. Kuo *et al.* (2007) presented lateral growth of a carbon nanotube (CNT) between two electrodes and its use as a nano temperature sensor. The fabrication of electrodes is carried out by micro-electromechanical systems techniques. The CNT is grown selectively by microwave plasma chemical vapour deposition between two electrodes.

Humidity detection

Sensors exhibit excellent sensing characteristics, such as ultrafast response and recovery times, good reproducibility, linearity, and environmental stability, which are important for applications in humidity monitoring and control. Research into nanosensors being used to detect humidity or changes in temperature resulting from humidity include:

- highly sensitive and stable humidity nanosensors based on LiCl-doped TiO2 electrospun nanofibres (Li *et al.*, 2008b);
- a novel sensitive humidity nanosensor based on an Na(+)-doped ZnO nanofibre membrane has been prepared via electrospinning and calcination (Hongnan *et al.*, 2010);
- a relative humidity sensor, using the dielectrophoretically located self-grown ZnO nano-materials as sensing elements, has been fabricated and the sensing properties tested (Liu *et al.*, 2008). It confirms that dielectrophoresis can fulfil the application of nano-materials in the field of sensors;
- humidity sensing using low-drift chemical sensing, which is applicable at the micro and nanometer scale, based on a new, all-differential approach (Cobianu *et al.*, 2010).

6. Nanotechnology in food tracking and tracing

Nanotechnology can enhance food safety by providing improving supply chain visibility, food authenticity, tracking and traceability through features that assist avoid counterfeiting, product adulteration and diversion (FAO/WHO, 2010; Neethirajan and Jayas, 2011; Lu and Bowles, 2013). To help in the tracking and tracing, nanotechnology provides complex invisible nanobarcodes with batch information that can be encrypted directly onto the food products and packaging. This nanobarcode technology facilitates 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).

For instance, Oxonica, Oxford, UK, offers solutions for food product identification using a biological fingerprint combined with recorded quality characteristics in the form of nanobarcodes. The technology involves nanoparticles made up of gold, silver, and platinum varying in width, length, and amount to create stripes of different degrees of reflectivity. By altering the stripe orders, different codes can be created and assigned to every food item, providing brand and authenticity in tracing food batches (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 functionalised 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 *et al.*, 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 *et al.*, 2005). Dip pen nanolithography involves using a scanning probe molecule-coated tip to deposit a chemically engineered ink material to create nanolithographic patterns on the food surface (Zhang *et al.*, 2009).

Röhrig 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.

Radio frequency identification (RFID) technology is a widely deployed and globally appreciated as a major technological enhancement to the management of tracking, information collection and reporting within a supply chain. However, appreciation of the advantages of combining RFID with nanotechnology is still emergent. Through experimentation and analysis of results using multiple variables, Mapa *et al.* (2010) confirmed the improved readability of RFID tags in the presence of various nanofluids at different concentrations on a conveyor belt, which is a typical packaging environment.

Watson *et al.* (2011) concluded that refinements to the use of RFID tags with nanotechnologies used on food 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).

Other developments have seen bar code and RFID technology being complemented or replaced by a nanobarcode that can be detected under ultraviolet light in a combination of colours that can be read by a computer scanner (Li *et al.*, 2005).

A self-powering approach developed by Wang (2010) which with a new paradigm in nanotechnology for truly achieving sustainable self-sufficient micro/nano-systems, which are of critical importance for sensing, infrastructure/environmental monitoring, defence technology, and even personal electronics. Self-powered sensors, meanwhile, are needed for monitoring oil/gas transportation lines over long distances.

Such a real-time network enables dynamic management by everyone involved because automated event-and-exception alerts allow trading partners – from the manufacturing facility to the end-user – to adjust their plans when unforeseen events happen, as opposed to after the fact, when it is too late. This is especially important for perishable foods, for which an immediate response is necessary to ensure safe passage throughout the supply chain.

7. Potential risk of nanotechnology in food supply chain

Nanotechnology has gained more and more attentions for its applications in food supply chain safety. At the same time, however, most food supply chain related applications are currently at R&D stage. There are also a number of knowledge gaps in our current understanding of the properties, behaviour and effects of nanotechnology, which make it difficult to assess the potential risk, researches have revealed that even more attention should be paid for the negative aspects of the technology (Chaudhry, 2010; Flari *et al.*, 2011). Consumers are also very worried about their safety on the application of nanotechnology in food supply chain (Bieberstein *et al.*, 2013).

In response to the rapid developments in the field of nanotechnology, numerous national and international discussion initiatives and projects have been undertaken, and generic data requirements and guidance for risk assessment of nanotechnologies have been presented in various reports over the last few years (Huyghebaert. *et al.*, 2010). For example, within the OECD Working Party on Manufactured Nanomaterials the Sponsorship Programme for the Testing of Manufactured Nanomaterials was established to evaluate whether the existing OECD test guidelines developed for chemicals may also be useful for the safety evaluation and risk assessment of nanomaterials (Bleeker *et al.*, 2013; OECD, 2012). Some types of fibrous nanometres such as carbon nanotubes and nano-fibers may present a risk similar to that of asbestos. Some carbon or metal based Nanomaterials may threaten the environment due to their bioaccumulative nature within food webs (Wang *et al.*, 2013).

Wang *et al.* (2013) reviewed toxic effects and potential risks of Nanotechnology, due to the minute unit size and large surface areas of nanotechnology, they may penetrate the body and individual cells (Elias *et al.*, 2002; Panyam *et al.*, 2003) and facilitate the direct generation of harmful radical oxygen species inside the cell (Brunet *et al.*, 2009; Sayes *et al.*, 2005; Shinohara *et al.*, 2009). Interactions with other transition metals and organic pollutants could enhance the toxicity and bioaccumulation of both nanotechnology and other contaminants (Arnall, 2003; Baun *et al.*, 2008; Brausch *et al.*, 2010; Cheng *et al.*, 2004; Wang *et al.*, 2013).

In order to reduce environmental and human health risks associated with Nanotechnology, proactive legislation to regulate the use of Nanotechnology is necessary. However, regulation of nanotechnology is in its infancy. None of the world's four leading public sector investors (Australia, Japan, UK, USA) are regulating nanotechnology beyond the realm of laws intended to govern the environmental and human health effects of traditional chemicals (Bowman and Hodge, 2007). Rather, regulation of nanotechnology is primarily limited to that in place for address bulk or powder form of chemicals (Bowman and Hodge, 2007). While specific legislation aimed at regulating Nanotechnology is lacking, there are international and national mechanisms in place which provide a rudimentary governance of nanotechnology that can evolve as we develop a better understanding of the fundamental and environmental and health properties of Nanotechnology (Wang *et al.*, 2013).

Limitations of current legislations on Nanotechnology may cascade into risks throughout raw-material production, manufacture, distribution, use and disposal processes. An effective and sustainable governance approach to nanotechnology should be based upon scientific research that fills basic knowledge gaps and improves life cycle assessment which may allow us to more fully understand the impacts of Nanotechnology to the environment and human health (Wang *et al.*, 2013).

8. Discussion and conclusions

Food supply chain involve many aspects such as planting, breeding, production, processing, transportation, storage, tracking and tracing, the process is complex and difficult to monitor and manage. The same time, the food itself has biochemical character of the resulting many recessive unsafe factors, lead to difficult to be detect the safety level. In addition, the storage and transportation time in food supply chain is demanding. Therefore, compare with generic supply chain, food supply chain need more sophisticated and sensitive equipment and technology.

Nanotechnology as one of the most market potential of emerging science and technology, its potential is undeniable. Nanotechnology in the field of medicine, materials, information and communications technology as well as environmental protection and energy development has seen a large number of applications. In September

2003, the application of nanotechnology in agriculture and food industry was first proposed by the United States Department of Agriculture, and predicted that nanotechnology will change the traditional method of food production, processing, packaging, transport and consumption, thereby changing the entire food industry. So far, researchers have conducted a large number of studies have shown that nanotechnology has potential applications in the food supply chain.

This paper reviewed the current and potential application of nanotechnology to the food safety management in supply chain from vary point of view, include food quality monitor, packaging, storage and distribution, tracking and tracing, in the last, we discussed the potential risk of nanotechnology to food supply chain. From this paper, we know that nanotechnology has potential application in every aspect of the food safety management in supply chain.

Compared with other technologies, nanotechnology has embedability and greater plasticity. Potential applications of engineered nanomaterials in food safety during supply chain include monitoring of food quality and biosecurity. Food packaging and quality control is a hot topic in nanotechnology R&D in the field of food, the first substantial applications of Nanotechnology in the food industry began in nanomaterials applied to food packaging. Nanotechnology deployment in food packaging and safety solutions has tended to focus more on food safety, by examining how it can be used to control microbial growth, delay oxidation, and create more convenience. To food safety in storage and distribution, Nanotechnology can be applied mainly for the detection of environmental and quality changes such as temperature, humidity or odour. At the same time, Nanotechnology can enhance food safety by providing improving supply chain visibility, food authenticity, tracking and traceability through features that assist avoid counterfeiting, product adulteration and diversion.

However, currently academia is still a lack of a systematic study of the toxicity of nanomaterials, the results of the safety evaluation of macroscopic matter in the past may not apply to nanomaterials. So far, only a few countries have developed some norms to adjust its development, not yet formed international technical standards to regulate the development and application of nanotechnology products. With the wide application of nanotechnology in the food supply chain, people come into contact with more and more nanomaterials through food. We have the necessary to give enough attention and discussion to potential impact of nanotechnology to human through food, and provide a scientific basis for human rational application of nanotechnology in the food supply chain.

Although the applications of nanotechnology in the food supply chain safety issues there are still uncertainties, while also facing the big problem of public acceptance. But after years of research and development of nanotechnology has made a lot of progress and development, and has been used in various fields of the food supply chain. Nanotechnology its special properties can not only improve the food safety in supply chain and improve the efficiency of the supply chain.

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