Trends in Food Science & Technology 72 (2018) 62–73

Contents lists available at ScienceDirect

Trends in Food Science & Technology

journal homepage: www.elsevier.com/locate/tifs

Review

Nanotechnology in the food sector and potential applications for the poultry industry

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ARTICLE INFO

Keywords:
Nanotechnology
Nanoparticles
Poultry
Chicken
Poultry processing plant
Food safety

ABSTRACT

Background: Salmonellosis and campylobacteriosis are among the most frequently reported foodborne diseases worldwide. Commercial chicken meat has been identified as one of the most important food vehicles for *Salmonella* and *Campylobacter* infection. Increased poultry consumption has forced producers to explore methods for increasing their production output, while maintaining the affordability and safety of their products. While the forecast benefits of nanotechnology have yet to be fully realised, it has potential application at many points along the food production chain and offers the opportunity to meet these challenges.

Scope and approach: The commercial poultry processing environment plays a significant role in reducing foodborne pathogens and spoilage organisms from poultry products prior to being supplied to consumers. This review discusses the potential opportunities and challenges for adopting nano-enabled technologies in the poultry industry, with respect to applications in microbiological food safety and quality assurance in the processing plant.

Key findings and conclusions: Several possibilities exist to exploit the benefits of nanotechnologies in the poultry processing plant to enhance the microbiological safety and quality of products. Those applications include the adoption of nano-enabled disinfectants, surface biocides, protective clothing, air and water filters, packaging, biosensors and rapid detection methods for contaminants, and technologies that assure the authenticity and traceability of products. Although the fate and potential toxicity of nanomaterials are not fully understood at this time and scientific risk assessments are required, it is evident that there have been significant advances in the application of novel nanotechnologies in the food industry.

1. Introduction

Current global predictions assert that by 2025 poultry meat will have the highest level of production and consumption, over beef, veal, pork and sheep (OECD/FAO, 2016) (Table 1). Poultry meat is already the most consumed meat in OECD countries (OECD., 2014). Increased poultry consumption may be attributed to the fact that chicken meat is an affordable and accessible source of protein with a low fat content, and that there are few religious or cultural barriers related to its consumption. Ease of cooking has also contributed to poultry meat becoming more popular among consumers (Haley, 2001). The global population is expected to reach 9 billion by the year 2050, and based on recent trends this, as well as increased income growth among poorer populations, will lead to an unprecedented increase in demand for animal protein (King et al., 2017). In light of this, the poultry industry has an important part to play in the provision of a sustainable food supply. This is due to the fact that chickens have a high feed conversion efficiency in comparison with other birds or livestock (FAO, 2010), raise more food on less land with less input than any other terrestrial food animal industries (FAO, 2010) and, relative to other sources of dietary protein, chicken meat is also a low greenhouse gas emission food (Caro, Davis, Bastianoni, & Caldeira, 2017). Growing consumer demand for affordable and safe food and the need for a sustainable food supply will continue to force producers to explore methods for increasing their production output. Novel advances in science and technology are essential to realizing economically viable solutions to these challenges.

Nanotechnology has emerged as a technological advancement to develop and transform the agrifood sector, with the potential to increase global food production, in addition to the nutritional value, quality and safety of food (Handford et al., 2014; Peters et al., 2016; Bhupinder Singh Sekhon, 2014). While a number of definitions of

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https://doi.org/10.1016/j.tifs.2017.11.015
Received 6 June 2017; Received in revised form 20 September 2017; Accepted 24 November 2017

Table 1
World meat projections.[a]

	Units	2017	2025
Beef and veal			
Production	kt cwe	69 942	75 496
Consumption	kt cwe	69 723	75 196
Pork			
Production	kt cwe	117 975	126 685
Consumption	kt cwe	117 931	126 679
Poultry			
Production	kt rtc	118 080	130 256
Consumption	kt rtc	118 081	130 254
Sheep			
Production	kt cwe	14 711	17 237
Consumption	kt cwe	14 712	17 238
Total Meat			
Per capita consumption[b]	kg rwt	34.3	34.6

[a] Based on data from OECD (2017), Table 3A1.4. World meat projections, in OECD-FAO Agricultural Outlook 2017–2026, OECD Publishing, Paris. https://doi.org/10.1787/agr_outlook-2017-table70-en.

[b] Per capita consumption expressed in retail weight. Carcass weight to retail weight conversion factors of 0.7 for beef and veal, 0.78 for pork and 0.88 for both sheep meat and poultry meat.

nanomaterials have been proposed by different committees and authorities, this review will use the recommendation of the European Commission, whereby a nanomaterial is defined as "*a natural, incidental or manufactured material containing particles, in an unbound state or as an aggregate or as an agglomerate and where, for 50% or more of the particles in the number size distribution, one or more external dimensions is in the size range 1 nm–100 nm*" (EU., 2011). Engineered nanomaterials used in agriculture, feed and food can roughly be divided into inorganic, organic, and combined materials such as surface modified clays (Peters et al., 2016). Inorganic nanomaterials include metals, metal oxides, salts, full carbon-based materials such as carbon nanotubes, fullerenes, carbon black and clay (Peters et al., 2016). Food naturally contains nanostructured organic ingredients such as proteins, carbohydrates and fats, which usually self-assemble into higher-order structures (Peters et al., 2016). The same materials can also serve to build food-grade polymers or nano-encapsulates and nano-emulsions (Peters et al., 2016). Titanium dioxide (TiO_2) nanoparticles are the most commonly used metal oxide nanoparticles in various industrial and commercial products, including food (Weir, Westerhoff, Fabricius, Hristovski, & von Goetz, 2012). The TiO_2 food additive is often used as a whitening and brightening agent in confectionary (candies and chewing gum), white sauces and icing. While nanotechnology is currently contributing significantly to the development of a broad range of novel and innovative applications in the agrifood sector, one of the most common applications is in the area of nano-antimicrobials/biocides to enhance food safety (RIKILT/JRC, 2014). Silver nanoparticles and nanocomposites are the most widely used antimicrobial nanomaterials in the food industry (He & Hwang, 2016). Silver nanoparticles display biocidal activity against a broad range of Gram-positive and Gram-negative microorganisms, yeast, moulds and viruses (Peters et al., 2016). The antimicrobial activity of silver nanomaterials is mainly based on the following mechanisms: (a) release of silver ions which bind to electron donor groups in molecules containing sulphur, oxygen or nitrogen, (b) disruption of DNA replication and, (c) oxidative stress through the catalysis of reactive oxygen species (ROS) formation (Peters et al., 2016; Singh, Jairath, & Ahlawat, 2016).

In the poultry industry the foodborne pathogens of highest concern are *Salmonella* and *Campylobacter* (Batz, Hoffman, & Morris, 2011; EFSA., 2010; FSANZ/SARDI, 2010; Furukawa et al., 2017), which can be present in the gut content or skin of healthy birds, and might be carried onto the meat (Barbut, 2001). Fortunately, *Salmonella* and *Campylobacter* are heat sensitive and should not be transferred to humans if the meat is adequately prepared (Barbut, 2001). However, salmonellosis and campylobacteriosis are among the most frequently reported foodborne diseases worldwide (WHO., 2015). The median global number of foodborne illnesses and deaths attributed to *Campylobacter* spp. are 16% and 5%, respectively (WHO., 2015). While the median global number of foodborne illnesses and deaths attributed to non-typhoidal *S. enterica* are 13% and 14%, respectively (WHO., 2015). While numerous potential vehicles of transmission exist, commercial chicken meat has been identified as one of the most important food vehicles for these organisms (Batz et al., 2011; FAO/WHO, 2009). Therefore, the industry has adopted a farm-to-fork philosophy where it is recognized that minimizing contamination requires all parties to participate (Barbut, 2001). The process starts with the breeding stocks and continues through hatcheries, farms, feed mills, live-poultry pick-up and transport, processing plants, distribution channels and the consumer's own kitchen (Barbut, 2001). Several possibilities exist to exploit the benefits of nanotechnologies during different phases of the food chain, with the aim to improve the microbiological quality of food during production and processing. For example, a recent review has detailed the potential benefits of using nanoparticles as a poultry feed supplement (Gangadoo, Stanley, Hughes, Moore, & Chapman, 2016), and a recent report describes the biocidal properties and applications of nanosilver in the disinfection of chicken hatcheries (Banach, Tymczyna, Chmielowiec-Korzeniowska, & Pulit-Prociak, 2016). Post-farm gate, the commercial poultry processing environment also plays a significant role in reducing foodborne pathogens and spoilage organisms from poultry products prior to being supplied to consumers (Barbut, 2001). Therefore, the focus of the current review is on the challenges and potential opportunities for application of nanotechnology in the poultry industry processing plant as they apply to microbiological food safety and quality assurance. Specifically, we will focus on the most recent developments in nanotechnology in relation to nano-enabled disinfectants, surface biocides, protective clothing, air and water filters, packaging, biosensors and rapid detection methods for pathogens/toxins/pesticides, and technologies that assure the authenticity and traceability of products. Finally, while food nanotechnology offers attractive potential benefits, there are emerging concerns arising from its novel physicochemical properties (He & Hwang, 2016). As such, the safety concerns and regulatory policies surrounding the use of nanomaterials in the food industry are also briefly addressed.

2. Potential applications of nanotechnology in the poultry processing plant

Poultry processing plants use very similar processing steps, although variation at some critical points can impact the rate of carriage and populations of pathogens remaining on carcasses. The basic steps involved in a typical poultry processing plant are outlined in Fig. 1. It should be noted that this entire operation can be automated to varying degrees depending on factors such as capital investment, local labour costs and availability, and processing volumes (Barbut, 2015). In addition, some poultry processing plants may take delivery of pre-slaughtered poultry for further processing. In Australia, poultry processing plants kill and dress the poultry on the same site. However, depending on the plant, further processing (i.e. partial, fully cooked or par-cooked, deboning and/or crumbing) may be undertaken at a separate plant site.

In order to investigate the potential applications of nanotechnology in the poultry processing plant, several sources of information were reviewed: peer-reviewed published literature, patents, company websites, and several nano-inventories. The nano-inventories included the Nanotechnology Consumer Product Inventory (CPI), first created in 2005 by the Woodrow Wilson International Center for Scholars and the Project on Emerging Nanotechnology (PEN., 2013; Vance et al., 2015). It should be noted that the CPI is by no means comprehensive and includes those products with an "unsupported claim", based solely on a manufacturer's marketing claims (PEN., 2013; Vance et al., 2015). Also

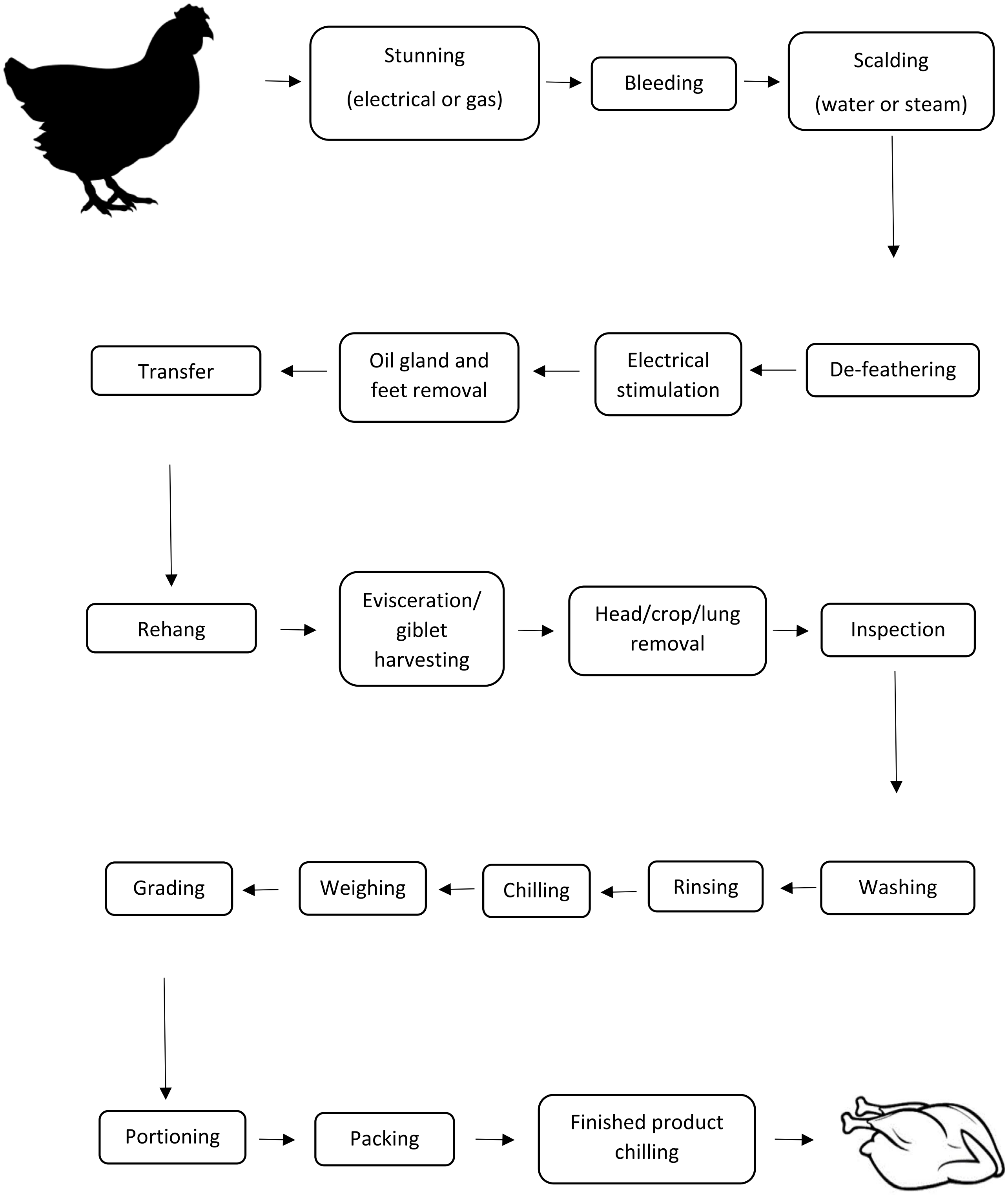

Fig. 1. The basic steps involved in a typical poultry processing plant.

consulted was the European Food Safety Authority (EFSA) commissioned inventory of currently used nanotechnologies in commercial products and in development applications in the agri/feed/food sector (RIKILT/JRC, 2014). Peer-reviewed, published papers were identified by electronic searches in Web of Science, PubMed and Google Scholar. The search strategy included different combinations of keywords such as "nanotechnology", "nanomaterials", "nanoparticles", "antimicrobial", "antibacterial", "food", "food industry", "food safety", "chicken meat safety", "poultry", "poultry industry", "chicken", "chicken meat", "*Salmonella*", "*Campylobacter*", "pork", "pork industry", "red meat", "red meat industry", "beef", "beef industry", "meat" and "agriculture". Eligible reviews were written in English and published after 2000. In addition, manual searches were performed in reference lists from published papers to find additional older studies that could have been overlooked by the electronic search. The same keywords were also used to conduct a patent search using Google Patent. After reviewing the literature, several categories were employed to summarize the various demonstrated and potential applications of nanotechnology in the poultry processing plant. These categories include their use as nano-enabled disinfectants, surface biocides, protective clothing, air and water filters, packaging, biosensors and rapid detection methods for contaminants, and technologies that assure the authenticity and traceability of products.

3. Disinfectants for equipment and production rooms

In the meat production environment, residual food left in processing machines and on food surfaces can cause microbiological recontamination of fresh food (Konopka, Kowalski, & Wzorek, 2009). However, the likelihood of food contamination is low when the processing line environment is kept properly clean by application of washing and disinfection processes (Konopka et al., 2009). As meat contains mainly protein, fat and moisture, alkaline solutions are the most common cleaning solutions used in poultry processing plants. Various cleaning compounds are available on the market, but commonly, an alkaline solution such as 1.5% sodium hydroxide is used (Barbut, 2001). Various alkaline phosphates and synthetic detergents are also used in meat processing plants to remove meat deposits, fat and dirt (Barbut, 2001). They are later washed away with water and the remaining scale deposits are removed with a weak/strong acid (Barbut, 2001).

The widespread use of disinfectant products has long prompted speculation on the development of microbial resistance (Ortega Morente et al., 2013). Resistance of bacterial organisms and other microorganisms to conventional disinfecting agents will require novel solutions in this field. New technologies, including nanomaterials with antimicrobial activity, have been used for efficient disinfection and microbial control. A number of products are commercially available, such as NanoCid® L2000 (Nano Nasb Pars Company, Tehran, Iran). NanoCid® L2000 is a nanosilver product reported to show strong antibacterial effect on four important foodborne pathogens; *Escherichia coli* O157:H7 (minimum inhibitory concentration (MIC) = 3.12 μg/mL, minimum bactericidal concentration (MBC) = 6.25 μg/mL), *Listeria monocytogenes* (MIC = 6.25 μg/mL, MBC = 6.25 μg/mL), *Salmonella typhimurium* (MIC = 3.12 μg/mL, MBC = 6.25 μg/mL) and *Vibrio parahaemolyticus* (MIC = 3.12 μg/mL, MBC = 6.25 μg/mL) (Zarei, Jamnejad, & Khajehali, 2014). As of 2017, the Nanotechnology Consumer Product Inventory (PEN., 2013) listed a number of other companies as producing nano-enabled disinfectant solutions, including EnviroSystems®, Inc. (USA), Green Earth Technologies, Inc. (USA), Purest Colloids, Inc. (USA), Silver Nano Technologies, Inc. (USA), Huzheng Nano Technology Co., Ltd (China), Daido Corporation (Japan), Lion® (Japan), SongSing Nano Technology Co., Ltd. (Taiwan), Inspiraz (Singapore), GNS Nanogist (Korea), Gaia Infonet Co., Ltd. (Korea), Bestnano Handels GmbH (Austria) and Nanobiz (Poland). The main antimicrobial agent listed in the majority of these products is nanosilver (PEN., 2013).

In the food production environment, care needs to be taken to ensure that nano-disinfectants do not enter landfill waste and wastewater streams, by way of fluids released from flushing and cleaning of processing equipment and contaminated surfaces and improper treatment of processing waste (EPA., 2012). One solution to this potential issue could be the use of Engineered Water Nanostructures (EWNS), produced by electrospraying water vapor, for applications in air and on surfaces (Pyrgiotakis, McDevitt, Yamauchi, & Demokritou, 2012; Pyrgiotakis et al., 2015, 2016). EWNS have an average of 10 electrons per structure and an average nanoscale size of 25 nm (Pyrgiotakis et al., 2012, 2014). This novel, chemical-free, and environmentally friendly alternative to existing disinfection methods, holds promise for development and application in the food industry (Pyrgiotakis et al., 2015). EWNS possess a unique set of physicochemical and biological properties; they contain Reactive Oxygen Species (ROS), have a very strong surface charge, are highly mobile, remain airborne in indoor conditions for hours, and interact and inactivate microorganisms on surfaces and in the air by delivering ROS. Their high surface charge makes possible the targeted delivery of the EWNS on the surface of interest, maximizing their efficiency. EWNS has been shown to be effective in inactivation of *E. coli*, *Salmonella enterica* and *Listeria innocua* on stainless steel surfaces and on organic tomatoes, without affecting the sensory quality of food (Pyrgiotakis et al., 2015). Most promisingly, the EWNS disintegrate back into water vapor, leaving no chemical residues (Pyrgiotakis et al., 2015). In addition, it has very low power demands and has been shown by an acute inhalation toxicological study to possess no apparent health effects to humans when EWNS are inhaled (Pyrgiotakis et al., 2014). However, further refinement of this technology is required in order to demonstrate safety and to be able to scale up this new food decontamination method for industrial purposes.

4. Surface biocides

Food contact surfaces comprise all surfaces that may come into contact with food products during production, processing, and packaging. The majority of foodborne illness outbreaks can be linked to cross-contamination events through contact with contaminated food contact surfaces (Griffith, Neethirajan, & Warriner, 2015). Spilled foodstuffs or runoff from carcass eviscerations contain a complex blend of carbohydrates, proteins, lipids and sugars, providing an ideal medium for bacteria to survive and thrive (Brown et al., 2014). Biofilms formed by pathogenic and spoilage bacteria may create a persistent source of product contamination. Biofilms support the survival of bacteria in suboptimal conditions and increase resistance to disinfectants and antimicrobials (Brown et al., 2014). The acidic biofilm environment also causes biofouling of equipment such as surfaces, chutes, cutting tables, tube systems, pipes and conveyor belts. The resulting corrosion, equipment impairment and reduced heat transfer efficiency may cause equipment to require more frequent maintenance and replacement. The most effective ways to inhibit biofilm formation is to prevent bacterial adhesion on the surface, which is a critical step of colonization (Das et al., 2013). Control of bacterial adhesion on surfaces by coating with antimicrobial agent is therefore crucial for designing antifouling materials. There is a sustained interest in developing antimicrobial coatings to reduce contamination levels (Griffith et al., 2015), with nano-engineered surfaces showing the potential to prevent the growth of biofilms and increase food safety. In the poultry processing environment, surface biocides may have a useful function in preventing clogging of processing machines and food processing and handling equipment that is difficult to clean (e.g. conveyor belts, refrigerators, storage containers). In addition, surface biocides may lower production costs by enabling more effective and less usage of cleaning and disinfectant products, as well as reducing the need for both cleaning and machine downtime.

Such antimicrobial surfaces utilize nanoscale metals such as silver, and photocatalytic metal oxide nanoparticles (such as titanium dioxide and zinc oxide), or nanoscale topography that allows the creation of surfaces with anti-fouling properties (Eleftheriadou, Pyrgiotakis, & Demokritou, 2017). Nano-silver refrigerators [Daewoo® and Samsung®] and cutting boards utilizing this principle are already commercially available [Pro-Idee GmbH & Co. KG (Germany) and A-DO Global (Korea)] (PEN., 2013). Nano-coatings for photocatalytic sterilisation of surfaces and water are also nearing market. For example, Green Earth Nano Science, Inc., a Canadian environmental and nanotechnology solutions developer, has approval from the Canadian Food Inspection Agency (CIFA) for its Gens Nano self-sanitizing photocatalyst coating. Gens Nano uses titanium dioxide for surface purification in combination with UV-C ultraviolet light, and is recommended as an environment friendly solution to surface and air bio-contamination risks faced by food processing facilities, food transportation, poultry farming and public buildings (GreenEarthNanoScienceInc., 2016). Photocatalysis requires light (commonly UV at 350 nm) and an appropriate surface to create pairs of reactive oxygen species (ROS) that oxidize and damage organic matter, including bacteria (Eleftheriadou et al., 2017). The use of UV light is a major limitation for photocatalytic surfaces but in recent years photocatalytic nanoparticles using visible light have been developed (S. Banerjee et al., 2014; Eleftheriadou et al., 2017). For example, research has been undertaken to develop visible-light-active photocatalysis by chemical modification of TiO_2 (S. Banerjee et al., 2014). Under visible light, dye sensitization of ZnO nanoparticles with chlorophyllin (Chl) has been reported to be effective against *E. coli* and suggests practical applications for the microbial decontamination of surfaces within the food manufacturing and processing environment (Aponiene & Luksiene, 2015). Doping TiO_2 nanoparticles with copper under visible light was shown to be effective against *E. coli* and *S. aureus*, indicating potential applications in wastewater treatment (Yadav et al., 2014). Also under visible light, the deposition of silver nanoparticles on bismuth vanadate ($BiVO_4$) has been reported to be effective against *E. coli* and suggests a promising method of enhancing the photocatalytic inactivation of bacteria in water (Booshehri, Chun-Kiat Goh, Hong, Jiang, & Xu, 2014).

5. Protective clothing

Other potential sources of contamination in the poultry processing environment include employees spreading bacteria via clothing or their movement from one area of a slaughter plant to another (FSIS., 2008). A range of nano-silver clothing items are available, including trousers (Contourwear, USA), socks (AgActive, UK; JR Nanotech PLC, UK; NanoTrade, Czech Republic; Vital Age, USA; Sharper Image®, USA; ArcticShield®, USA; Lexon Nanotech, Inc., USA; AgActive, UK; AgActive, Australia; SongSing Nano Technology Co., Ltd., Taiwan; Nano-Infinity Nanotech Co., Ltd., Taiwan), coats (Sanyo-Shokai, Japan) and face-masks (Emergency Filtration Products, USA; Nanux Co., Ltd., Korea). Several companies make a range of different clothing items (Goodweaver Textiles Co. Ltd., Taiwan; NanoTrade, Czech Republic; Greenyarn LLC., USA; Nanbabies®, USA; SilberSchutz, Germany; Jack Wolfskin, Germany) and nano fabric (Macker International Apparel Inc., Canada; Tianjin Rongze Textile Co., Ltd., China; Mipan®, Korea; Miyuki Keorki Co., Japan) (PEN., 2013). In parallel to the development of nanotextiles, life cycle assessments have been undertaken. A recent review identified several research gaps in the life cycle considerations for silver nanoparticle textiles (Hicks, Gilbertson, Yamani, Theis, & Zimmerman, 2015). These research gaps included the fact that the relationship between silver nanoparticle concentration in textiles and the functional efficacy is not yet fully understood. As a result, there is significant variability in the initial silver concentrations of commercially available silver nanoparticle textiles. While silver release during different laundering conditions has received the most focus (i.e. detergent, bleach, water temperature, water chemistry and laundering methodology), the greatest variability in silver release is most likely associated with the silver attachment method. Determining the antibacterial performance and lifespan of each nano-enabled clothing item will require assessments that take these considerations into account.

6. Air and water filters

Air plays a significant role in the transmission of pathogens and may be implicated in contamination of poultry meat at various stages of slaughtering and processing (Liang et al., 2013; Lues, Theron, Venter, & Rasephei, 2007; Whyte, Collins, McGill, Monahan, & O'Mahony, 2001). The highest counts of microorganisms have been recorded in the initial stages of processing, i.e., the receiving-hanging and defeathering areas, with a definite decline toward the evisceration, prechilling, subdividing, and packing areas (Liang et al., 2013; Lues et al., 2007; Whyte et al., 2001). Brincat et al. (2016) reviewed and evaluated currently available air filtration technologies used in cold storage food warehouses and reported that nanofiber mats represent an emerging technology which might become more prevalent in use worldwide in the coming years. Nanofiber mats have been impregnated with fungicidal or bactericidal materials, including silver or other metals, and display a high antimicrobial efficiency due to their relatively large surface area for functionalization. However, the very high efficiency of these mats at very small particle size might be a disadvantage as the filter would become fully loaded more quickly and need to be replaced at higher frequency (Brincat et al., 2016). Air filters employing nanomaterials (mainly silver) and claiming antimicrobial properties are already commercially available from C & C Co., Ltd. (Korea), Airo Co., Ltd. (Korea), Shinah Electronics Co., Ltd. (Korea), Clean Air Technology Corp. (Korea), Samsung (Korea), SongSing Nano Technology Co., Ltd. (Taiwan), Kind Home Ind. Co. Ltd. (Taiwan), Transit Electronics Co., Ltd. (China), US Global Nanospace, Inc. (USA) and Winix Inc. (USA) (PEN., 2013).

The poultry industry uses a considerable amount of water throughout processing, particularly in the scalding and chiller unit operations. Conditions in the scalder and chillers must be correctly maintained, otherwise they can be a major source of cross-contamination between carcasses (FAO/WHO, 2009). The food industry has made great progress in purification of water through the use of nanoparticles (Bhupinder Singh Sekhon, 2014). The CPI lists two commercially available water filtration units from Bielmeier (Germany) and Seldon Laboratories, Inc. (USA) (PEN., 2013).

Water filtration is also required for waste management, as water used for scalding, washing carcasses, salvaging giblets and cleaning the poultry processing plant cannot simply be discharged into lakes and rivers because of the relatively high content of organic matter such as protein and fat, and the microorganisms present (Barbut, 2001). This water must receive some level of treatment before it can be discharged into on-site or municipal water treatment facilities. Different procedures can be used, ranging from simple filtration to sophisticated aerobic lagoons (Barbut, 2001). Nanomaterials are fast emerging as potential candidates for water treatment in place of conventional technologies which, notwithstanding their efficacy, are often very expensive and time consuming (Bhattacharya et al., 2013). Most nanotechnology applications in water treatment are still in the stage of laboratory research (Rodrigues et al., 2017). However, there are a few pilot and field tests and several commercially available nanotechnologies for water treatment or resource recovery (e.g. nanoadsorbents, nano-enabled membranes, nanophotocatalysts or nano-enabled disinfection systems) (Rodrigues et al., 2017).

While there are considerable challenges in the development of nanotechnology applications in agricultural wastewater treatment, including achieving selectivity for specific compounds (e.g. by tailoring atomic structures) and high organic loads (Rodrigues et al., 2017), there is at least one promising application currently in development for the poultry industry. One of the main challenges for the poultry industry is the amount of phosphorus present in poultry waste water streams and the requirement to reduce the amount of phosphate (the inorganic form of phosphorus) in processing wastewater prior to discharge (PoultryTech, 2015). In most poultry processing plants, aluminum, iron, or calcium-based coagulants are used to remove phosphate from wastewater. However, this process has its drawbacks due in large part to the costs associated with the use of metal salts and the resulting biosolids, which create an additional treatment problem. Researchers at the Georgia Tech Research Institute (GTRI) have developed a proprietary phosphate removal chemistry, which is applied to the surface of a magnetized nanoparticle to specifically attach phosphate molecules (PoultryTech, 2015). The phosphate-attached magnetized nanoparticles can then be easily removed by an external magnet and the whole process can be conducted in a continuous flow-through device. This method can be used as the primary step for phosphate removal or as a refining step to remove excess phosphate from wastewater streams where a less efficient removal method has been used. The ultimate aim is to provide the poultry industry with a low-cost alternative to current phosphate removal technology. A number of other published studies have also described various methods employing nanotechnology for phosphate removal from water (for example: (Abo Markeb, Alonso, Dorado, Sánchez, & Font, 2016; J.-H. Kim, Kim, Lee, & Choi, 2017)).

7. Packaging

Undeniably, the most active area of food nanotechnology research and development is packaging (Duncan, 2011; Panea, Ripoll, González, Fernández-Cuello, & Albertí, 2014; Ranjan et al., 2014). The appropriate packaging of poultry meat products is vital if food safety and product shelf-life are to be guaranteed (Panea et al., 2014). While retail packaging is the most obvious example of packaging material which comes into contact with foodstuffs, there are other important applications of food contact materials which include sacks, bags, drums, boxes, crates, tanks, tubing, conveyor belts and the like (Bradley, Castle, & Chaudhry, 2011). However, these have received far less attention compared to the R&D expended on nano-enabled applications for retail food packaging (Bradley et al., 2011). The feasibility and benefits of adopting nanotechnology in food contact materials other than retail food packaging (i.e. conveyor belts) is worthy of further investigation, as the contact time with the poultry product would be minimal and therefore migration or carry-over to food is expected to be excluded and exposure is therefore anticipated to be negligible (RIKILT/JRC, 2014). The use of nanotechnology in food contact materials in the further processing plant (FPP) could also offer great benefit, particularly as an antimicrobial intervention against *Listeria* (Berrang, Meinersmann, Frank, & Ladely, 2010).

While the results of a patent search provided no direct evidence that nanomaterials are currently being used in food packaging applications in Australia and/or New Zealand, there is evidence they are being used overseas (Drew & Hagen, 2016). A number of patents exist for the use of nanoparticles in food packaging in Europe, the United States and Asia (Drew & Hagen, 2016). The two nanomaterials with the most patents are nano-clays and nanosilver (Drew & Hagen, 2016). Current applications of nanomaterials in food packaging include the enhancement of barrier properties through the incorporation of nano-fillers (e.g. nanoclay), 'active' food packaging; with intentional controlled release of active substances such as antibacterials to improve the shelf-life of food (e.g. nanosilver) and, improvement of physical characteristics to make the packaging more tensile, durable, or thermally stable (e.g. nano-titanium dioxide, titanium nitride) (Drew & Hagen, 2016). Potential future applications include the use of 'smart' packaging (e.g. nanosensors and labels) (Drew & Hagen, 2016). For those active and smart packaging applications requiring unique and costly materials or processes, the benefits of these technologies will most likely limit market penetration to premium and relatively high-margin food products for which the cost-benefit analysis is financially sustainable (Werner, Koontz, & Goddard, 2017). Active and smart packaging applications are discussed in more detail below.

The incorporation of active compounds into food packaging materials where they are bound rather than designed to migrate are more common than packaging designed to release particulate nanomaterials into foods (Cushen, Kerry, Morris, Cruz-Romero, & Cummins, 2012). However, a critical issue is the unintentional transfer of packaging materials into the food. Nanomaterial migration can occur through mechanisms such as, dissolution of the compound in a food, actual diffusion of particles or transfer through abrasive action on the surface of the food contact material. This problem may influence the food's safety and, subsequently, consumers' health. It also can cause undesirable organoleptic changes in the food. Therefore, for new food packaging products containing nanomaterials, it is necessary to conduct migration experiments on a case-by-case basis (Drew & Hagen, 2016). Several studies have demonstrated the potential benefits of adopting active packaging for poultry products (Akbar & Anal, 2014; Dias et al., 2013; Morsy, Khalaf, Sharoba, El-Tanahi, & Cutter, 2014; Panea et al., 2014). Akbar and Anal (2014) reported that zinc oxide nanoparticles film-embedded in active packaging in a challenge study on ready-to-eat poultry meat sausages against *Salmonella typhimurium* and *Staphylococcus aureus* resulted in a substantial reduction in the number of inoculated target bacteria. Dias et al. (2013) reported that antimicrobial packaging incorporating allyl isothiocyanate and carbon nanotubes enabled effective storage of shredded cooked chicken meat for 40 days by reducing microbial contamination, controlling oxidation and reducing colour changes. Morsy et al. (2014) demonstrated that silver and zinc oxide nanoparticles incorporated into pullulan films and applied to fresh or ready-to-eat turkey products can inhibit foodborne pathogens over three weeks of vacuum-packaged, refrigerated storage. Panea et al. (2014) delayed spoilage and lipid oxidation of chicken breasts packaged in low density polyethylene (LDPE) blended with silver and ZnO nanoparticles. In addition, absorbent pads are a common component in packaging strategies developed to extend the shelf-life of poultry meat (Fernández et al., 2009). Fernández et al. (2009) and Lloret, Picouet, and Fernández (2012) have reported on the effectiveness of absorbent pads containing silver nanoparticles in reducing the microbial load of poultry exudates (Fernández et al., 2009; Lloret et al., 2012).

Fresh produce or meats that are either spoiled or unpalatable exhibit odours, colours or other sensory characteristics which can be easily discerned by consumers (Duncan, 2011). However, when packaging materials prevent extensive sensory exposure, consumers must rely on use-by dates, which are determined by producers based on a set of assumptions about the way that the food is stored or transported (Duncan, 2011). Smart packaging incorporating nanosensors can be devised, which can detect the presence of gasses, aromas, chemical contaminants, spoilage accelerators such as temperature or light intensity, pathogens or products of microbial metabolism (Fuertes et al., 2016; Mlalila, Kadam, Swai, & Hilonga, 2016). The nanosensors can communicate this information about the food to the consumer or respond to the information and change conditions within the packaging to delay spoilage/contamination (Cushen et al., 2012). An example of the latter is a label for poultry meat based on a reaction between hydrogen sulphide and a nanolayer of silver (Smolander, Hurme, Koivisto, & Kivinen, 2004). Sulphur compounds are produced during the decay of poultry meat, such as chicken or turkey. The nanosilver layer is opaque light brown, but when meat starts to deteriorate silver sulphide is formed and the layer becomes transparent.

Nanocomposites are formed when a polymer matrix is reinforced with fillers in the nanoscale, resulting in improved packaging properties (Silvestre, Duraccio, & Cimmino, 2011). Some examples of fillers are clays, silicates, cellulose microfibrils, cellulose whiskers, and carbon nanotubes; while polymers include polyamide, polystyrene, nylon, polyolefins etc. (Ramachandraiah, Han, & Chin, 2015). Growing demand for the production of biodegradable packaging has also led to the use of biopolymers that may be natural or synthetic (Ramachandraiah et al., 2015). Nanocomposites can improve the mechanical strength, biodegradability properties, reduce weight, increase heat resistance, and/or improve barrier against oxygen, carbon dioxide, ultraviolet radiation, moisture, and volatiles of food package materials (Bhupinder S Sekhon, 2010). Better barrier properties can help maintain food quality and increase shelf life without the use of additional chemical preservatives (Bradley et al., 2011). For example, Bayer (Leverkusen, Germany) produces Durethan KU2-2601 packaging film that is enriched with silicate nanoparticles. These particles are dispersed throughout the film and reduce the entrance of oxygen and other gases, and the exit of moisture, thus protecting food from spoiling. This product is also stronger and more heat resistant than those currently on the market (Luo, Wu, & Zhi, 2016). In another study, Jang, Lim, and Song (2010) analysed *Gelidium corneum*–gelatin (GCG) film incorporating nano-clay and thymol. It was reported that this packaging material displayed greater tensile strength, reduced water vapour permeability and inhibited growth of *E. coli* O157:H7 and *L. monocytogenes* during storage of packed chicken breasts (Jang et al., 2010).

8. Nano-enabled technologies to establish authenticity and for traceability

For foods of animal origin, the basic authenticity concerns involve the substitution of high value raw materials with lower value materials such as cheaper pieces of meat, mechanically recovered meat, offal, blood, water, eggs, gluten or various other protein sources of animal or vegetable origin (Arvanitoyannis, 2016). Furthermore, the latter can also give rise to various food safety implications since addition of these products can lead to allergic reactions in certain individuals (Arvanitoyannis, 2016). Another aspect is the differentiation of frozen-and-thawed meat from fresh meat (Arvanitoyannis, 2016). The widespread avian influenza epidemic completely disrupted production and trade in many areas of the world and has heightened awareness of traceability and information flows in the poultry industry (Andreas & Beverley, 2007). Food safety and food quality are two very important elements of people's perceptions of food and associated decision-making (van Rijswijk & Frewer, 2006). Traceability of foods and its component parts is a powerful tool to help to establish authenticity, and to check the truthfulness of claims made by producers about their food and its safety (van Rijswijk & Frewer, 2006). Consumers might be especially interested in traceability when it is linked to assurances about the sources, quality and safety of food (van Rijswijk & Frewer, 2006). Aside from brand-protection, the benefits of enhanced traceability systems for industry are many and include: assurance of biosecurity protection of the national livestock population, compliance with requirements of the global food supply chain, increased efficiency of food safety investigations and product quality issues and minimisation of product recall, more effective control of incidents and crisis management, and increased and continuous improvement in the logistical aspects of the food supply chain (Manning, Baines, & Chadd, 2006). In addition, an increasing demand for higher value organic and traceable poultry products may lead to individual identification becoming a key component of the industry in the future (Mc Inerney, Corkery, Ayalew, Ward, & Mc Donnell, 2010). Nanotechnology may also be used for the detection of GMOs, with advances already made in the detection of transgenic rice varieties (Chen, Han, Luo, Wang, & Wang, 2012) and transgenic soy crops (Deng, Ge, Cao, & Han, 2011; Li et al., 2016).

Nanotechnology can help manufacturers to ensure the authenticity, traceability and safety of their food products. Nanotechnology provides complex invisible nanobarcodes with batch information which can be encrypted directly onto the food products and packaging (Neethirajan & Jayas, 2011). 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 & Jayas, 2011). Nanotechnologies can be embedded in a product to enable brand owners to assure customers of its authenticity and to include unique product information such as data about conditions collected from sensors during production, processing and/or transport (J. Lu & Bowles, 2013). This can not only inform buyers about food quality, but also confirm product pricing and assure greater security and safety if a product recall requires data relating to product origins (J. Lu & Bowles, 2013). A number of companies offer nanobarcoding solutions for food product identification and brand authenticity. For example, Oxonica (UK) produces unique reading strips for food items consisting of gold, silver, and platinum varying in width, length, and amount to create stripes of different reflectivity.

9. Nano-enabled sensors for rapid pathogen/contaminant detection

Food safety is threatened by pesticides and veterinary drug residues in food, use of illegal additives, heavy metals, organic compounds, pathogens and toxins (Zeng, Zhu, Du, & Lin, 2016). Conventional detection methods for biological and chemical contaminants are time-consuming and laborious, requiring specific sophisticated instruments and trained personnel (Stephen Inbaraj & Chen, 2016). Therefore there is a continued demand for new analytical technologies that can detect small concentrations of chemicals or microbes in a more cost- and time-effective manner, preferably in the field, on the production line, and/or non-destructively, with little to no sample pre-treatment, and preferably without the requirement for excessive training of staff (Wang & Duncan, 2017). The unique properties of nanoscale materials offer many opportunities to sensing science (Wang & Duncan, 2017), with nanosensors possessing several advantageous properties, such as high sensitivity and selectivity, near real-time detection, and low cost and portability (Magnuson, Jonaitis, & Card, 2011). For example, the large relative surface area of nanomaterials facilitates high recognition element densities, allowing for the efficient isolation and pre-concentration of analytes from complex matrices (Wang & Duncan, 2017). Larger specific surface areas also result in better immobilization of recognition molecules on nanostructured transducers, and thus faster transmission of detection events (Wang & Duncan, 2017). Aside from benefits related to surface area, nanostructured materials can also be engineered to have discriminating optical or electronic signatures, which can translate into gains in selectivity and sensitivity and introduce new opportunities for multiplexed detection (Wang & Duncan, 2017).

There are many scientific publications on nanosensors for the food industry; but only a few of these are commercially available. Nanosensors have been designed to detect and quantify many types of analytes relevant to the meat industry, including gasses, vapors and ions, small organic molecules, biomolecules, and a range of foodborne pathogens (T. Banerjee, Shelby, & Santra, 2017; Singh et al., 2016; Wang & Duncan, 2017). Relevant to the poultry meat industry, nanosensors have been developed for the detection of antibiotics in chicken tissue (Ahn & Lim, 2015; Long, Zhang, Yang, Zeng, & Jiang, 2015; C.; Lu, Tang, Liu, Kang, & Sun, 2015; Mungroo & Neethirajan, 2014; Peng, Duan, Pan, Liu, & Xue, 2013). In addition, nanosensors have been developed for the detection of a number of foodborne pathogens relevant to the poultry industry. For example, the use of nanosensors has been reported for the detection of *Salmonella* in chicken extract (G. Kim, Moon, Moh, & Lim, 2015); *Vibrio* and *Salmonella* (multiplex) in chicken breast (Duan et al., 2015); *E. coli*, *Listeria*, *Salmonella*, *S. aureus* in chicken rinse (Sundaram, Park, Kwon, & Lawrence, 2013) and, *Salmonella* Typhimurium in chicken carcass wash water (Yang & Li, 2005). While, Liu, Petty, Sazama, and Swager (2015) describe the application of nanosensors for the detection of biogenic amines (i.e. putrescine, cadaverine) in the monitoring of spoilage in raw chicken meat (Liu et al., 2015). Mycotoxins from mycotoxigenic fungi, may also be an issue in poultry feed for food-producing animals (Greco, Franchi, Rico Golba, Pardo, & Pose, 2014). The use of nanomaterials in the fabrication of nanobiosensors for the detection of mycotoxins in food and feed has been comprehensively reviewed (Rai, Jogee, & Ingle, 2015). Nanosensors have also been employed in the detection of several pesticide residues that are widely used in agriculture (S. Liu, Yuan, Yue, Zheng, & Tang, 2008; Xiang, Zhao, & Wang, 2011).

In a recent article, Britton (2016) expanded on how nanotechnology could in future revolutionize the rapid monitoring of biological contaminants in the poultry industry (Britton, 2016). While various chemical interventions are regularly applied to the chiller to reduce the microbial loading of the birds, one of the challenges for processing plants is to monitor the real-time effectiveness of these interventions (Britton, 2016). To do so effectively would require the ability to capture a representative sample of the very large chiller water volume and concentrate the bacteria or pathogens of interest for testing and evaluation (Britton, 2016). A potential solution could be the use of magnetic nanoparticles coated with the appropriate specific and selective attractant, which when mixed into a sample of the chiller water would attach to the bacteria of interest. A magnetic field could be used to capture both the nanoparticles and attached bacteria, while the remainder of the chiller water is drained from the system. Microbiological analysis of the captured bacteria could then be undertaken. Ideally, microbiological analysis could be conducted automatically on a side stream of the chiller, which would allow regular monitoring of the bacterial loading in the chiller. To provide real-time feedback control, however, would require the development of a rapid biosensor that can accurately distinguish between live and dead bacteria. Once this can be accomplished, the chiller systems could automatically dispense the appropriate dosages of chemical interventions based on the real-time readings from the water samples (Britton, 2016).

10. Cost to industry

Costs and capacity required to develop or access the nanotechnology are critical aspects for the adoption of any application by industry (Bradley et al., 2011). Generally, cost and technical barriers for the incorporation of nanomaterials in already existing technologies (e.g. for food packaging) are expected to be relatively low and easier to overcome than developing novel technologies (Bradley et al., 2011). Many recently developed nano-enabled systems in the food industry are proprietary and since development and production costs are not disclosed, an effective comparison of costs with conventional systems is not possible (Rodrigues et al., 2017). The cost required to enable commercialization is also application-dependent. A higher initial material or process cost is likely to promote adoption in applications that exploit multiple properties of the nanomaterial (Zurutuza & Marinelli, 2014), or where a premium and relatively high-margin food product is being produced (Werner et al., 2017). Undoubtedly, as R&D activities overcome technical difficulties and production costs fall, market penetration of nanotechnology applications will increase. While it is difficult to gauge the true scale of industrial activity in this area because of commercial and other sensitivities, it has been estimated that between 200 and 400 companies are undertaking research and/or using nanotechnology for food applications (Chaudhry, Castle, & Richard, 2017). It is therefore likely that many more products and applications that are currently in the R&D pipeline will appear on the market in coming years (Chaudhry et al., 2017).

11. Potential risks of nanotechnology

The rapid expansion of nanotechnology in the food chain and the predicted further increase, raise valid concerns regarding the potential adverse effects of nanomaterials on human health and the environment across their life cycle (Eleftheriadou et al., 2017; Sadeghi, Rodriguez, Yao, & Kokini, 2017; Servin & White, 2016). Nanoparticles have distinctly different physicochemical properties, behaviour and interactions, compared to their conventional form (Gallocchio, Belluco, & Ricci, 2015). As a consequence, the effects and impacts of nanoparticles on human health cannot necessarily be determined by extrapolating the existing knowledge on risks for larger sized particles having the same chemical composition (Gallocchio et al., 2015). Properties like solubility, bioavailabilty, biopersistence, aggregation and adsorption contribute to determining the potential ill effects of nanoparticles on human health. Different nanomaterials and different applications of a given nanomaterial could raise unique questions or issues, as well as some issues that are common to various applications of a given nanomaterial or even to different nanomaterials. Therefore, there is an urgent need to understand the relationship between the intrinsic properties of a nanoparticle, its physico-chemical transformation across the gastrointestinal tract and gastrointestinal fate, its potential toxicity, as well as its physicochemical and biological transformations once released into the environment.

Toxicity tests involve subjecting cells or organisms to a dose of chemicals and measuring the response over a period of time. The dose–response relationships obtained in these experiments are important because they are used for determining appropriate acceptable limits for exposure to the tested chemicals. As discussed previously, nanoscale silver particles are currently used in more manufacturer identified products than any other nanomaterial (PEN., 2013). The number of silver nanoparticle *in vivo* toxicological studies in mammalian model organisms (e.g. mice and rats) is still extremely small (for a Review see (Mao, Tsai, Chen, Yan, & Wang, 2016)). *In vivo* studies may also differ in the method of entry of the nanoparticle, whether by dermal contact, oral ingestion, respiratory inhalation or intravenous/intraperitoneal injection. Therefore, generalized conclusions about the effects of silver nanoparticle exposure via food-relevant routes of exposure remains limited. It is, for example, still unclear to what extent the biochemical pathways which facilitate processing of silver ions apply to silver nanoparticles, to what extent silver nanoparticles pass through the intestinal lining intact or are dissolved into silver ions in the highly acidic environment of the stomach, and to what extent silver nanoparticles can pass through natural biological barriers such as the blood–brain barrier (Duncan, 2011). It is also crucial to note that there have been almost no attempts to study the cumulative effects of chronic silver nanoparticle exposure, and systematic investigations of the relationship between particle characteristics (size, shape, surface charge, etc.) and toxicity have yet to be performed (Duncan, 2011). Therefore, there is an urgent need for additional toxicology studies of adequate design and duration on different types of nanomaterials to provide more conclusive evidence regarding the toxicity of nanomaterials used in food (Handford et al., 2014). Existing toxicity methodologies applied to conventional materials may require modification to consider the unique characteristics of nanoparticles (Handford et al., 2014). In relation to risk assessment, it is also important to note that toxicity is likely to vary among specific nanoparticles, thus, until predictive modelling of nanoparticle toxicity matures as a science (Winkler et al., 2014), a risk assessment potentially needs to be performed on a case by case basis (Handford et al., 2014).

It is also important to keep in mind that in determining the health impact of a nanoparticle present in a food contact material, toxicity information needs to be contextualized by a determination of how readily the nanoparticle is released into various foods substances (Duncan, 2011). As previously discussed, the most active area of food nanoscience research and development is packaging. Unfortunately, very little work has been done to assess the ability of nanoparticles in general, and silver nanoparticles in particular, to migrate through packaging materials and cross over the packaging/food interface (Duncan, 2011), as well as what happens to the physico-chemical characteristics of the particle after migration. In a report commissioned by Food Standards Australia New Zealand (FSANZ), the safety and regulation of nanotechnologies in food packaging was reviewed (Drew & Hagen, 2016). Safety assessment of nanomaterials used in food packaging first requires an understanding of potential exposure via migration into food. If there is no exposure, it follows there is no risk of adverse effects in consumers. Migration of nanomaterial constituents or the nanoparticles themselves from polymer nanocomposites into food or food simulants has been assessed by various authors using standard migration tests. These tests are European standardised methods used to evaluate migration from food packaging, and are carried out using different food simulant solutions characterised by varying levels of water solubility and acidity. The methods have not been validated for nanomaterials. There are various issues that complicate the interpretation of food packaging migration studies conducted with nanomaterials. These include uncertainty in the ability of the analytical techniques utilised to detect nanoparticles in food simulants (Picó, 2016), uncertainty in the influence of sample preparation methods and the often limited level of description provided of how these methods were carried out (Drew & Hagen, 2016). Drew and Hagen (2016) reported that their review indicated that for most of the studied nanomaterials in food packaging, migration of intact nanoparticles into food simulants is negligible, implying consumer exposure to these materials is likely to be low. Drew and Hagen (2016) concluded that if many of the metal oxide nanoparticulates were to migrate in nanoparticulate form, at the resulting low concentration in food that they would likely dissolve into their ionic forms upon contact with acid foods or stomach acid. Of course, these conclusions were tempered by the relatively few studies which have investigated the migration of nanoparticles from food packaging materials and the uncertainties in current analytical techniques for measuring possible migrated nanoparticles in food simulants (Drew & Hagen, 2016). In addition, while studies have been undertaken to improve methods of detection, characterization and quantification of nanoparticles in complex food samples, they are far from being incorporated into routine analysis (Laborda et al., 2016). Also in need of attention, is the assessment of the risk of contamination of food products with nanomaterials used in processing such as nanofiltration, non-fouling surfaces, or catalytic processes (Coles & Frewer, 2013).

12. Regulation of nanotechnology

The effective regulation of nanotechnologies in the food sector requires a clear regulatory target (Fletcher & Bartholomaeus, 2011). However, as highlighted previously, there is no internationally agreed definition of “nanomaterial” suitable for regulatory purposes. The major issue is that definitions that rely solely upon linear dimension as their basis do not provide a sound foundation for regulatory responses because they do not capture any concept of novelty or hazard (Fletcher & Bartholomaeus, 2011). Therefore, in responding to the increased sophistication of the nanotechnologies, the primary focus for Food Standards Australia New Zealand (FSANZ) is not on size of the material *per se*, but on materials likely to exhibit physicochemical and/or biological novelty (Fletcher & Bartholomaeus, 2011). Australian and New Zealand law requires that all food meet the food safety standards set out in the Australian New Zealand Food Standards Code, whether produced domestically or imported. Applications for new food substances manufactured using nanotechnologies, or incorporating novel nanoscale materials are evaluated under existing standards. FSANZ will conduct a thorough risk assessment on any application to approve the use of nanotechnology in food, in accordance with the Codex Risk Analysis Framework. To date, FSANZ has not yet received any applications to approve new or novel nanoscale particles for food use.

FSANZ has amended its Application Handbook to include food contact materials containing substances in the nanoscale. In other countries regulatory authorities have taken different approaches to managing the commercialisation of nanomaterial-containing food packaging, including guidance documents, specific regulation or amendment to existing regulations (Hannon, Kerry, Cruz-Romero, Morris, & Cummins, 2015).

13. Conclusions

Nanotechnology has been applied in various fields in the food industry with promising results, including in the areas of food packaging and food safety. Numerous opportunities exist to exploit the benefits of nanotechnologies within the poultry processing chain, to improve the microbiological quality and safety of food products. The most important application of nanotechnology in the food area for the near future is considered to be the incorporation of nanomaterials or nanotechnological devices in packaging materials or storage containers in order to lengthen product shelf-life while maintaining product stability (RIKILT/JRC, 2014). Indeed, Ramachandraiah et al. (2015) report that the most promising area for nanotechnology application is specifically meat packaging. Nanotechnology incorporated into other food production contact surfaces (i.e. food production machinery, filters, conveyor belts) also offer potential for the poultry processing industry. In the case of food contact surfaces, this application of nanotechnology is expected to have very low additional safety concerns, since migration or carry-over to food is expected to be excluded and exposure is therefore anticipated to be negligible (RIKILT/JRC, 2014). The poultry industry may also benefit from the use of nano-enabled disinfectants to reduce or prevent bacterial resistance and biofilm formation from routine treatment with disinfectants commonly used in the poultry processing plant. While still under development, the use of Engineered Water Nanostructures (EWNS), could offer a novel, chemical-free, and environmentally friendly alternative to existing disinfection methods. Future regulatory requirements and consumer expectations will also be more easily facilitated with nano-enabled biosensors, enabling rapid detection of contaminants, and assurance of the authenticity and traceability of products.

The application of nanotechnologies, however, requires careful consideration since toxicological data is lacking and the development of analytical methods able to guarantee consumer protection is still ongoing. The rapid developments make it necessary to continue detailed attention directed to design of risk assessments and how to deal with uncertainty surrounding potential risks. Food safety is one of the most important issues in marketing any kind of food, and poultry meat is no exception. If consumers perceive that a product is unsafe, all other positive selling points become irrelevant. Public perception of nanomaterials is therefore likely to be vital to the successful application of nanotechnology in the food industry (Cobb & Macoubrie, 2004; Lee, Scheufele, & Lewenstein, 2005; Ravichandran, 2010, pp. P72–P96). Concerns regarding labelling, product safety, health and environmental consequences of foods could significantly hinder consumer acceptance of nano-enabled foods (Rodrigues et al., 2017). This is aggravated further by the lack of comprehensive risk assessment and regulatory frameworks and unknowns regarding the way nanotechnology in the food sector will be handled by regulatory agencies in the future, particularly considering that for several cases, potential risks are still under evaluation (Rodrigues et al., 2017). The safety of new materials to workers and consumers, and the impacts of nanomaterials on food quality must be determined and be acceptable to consumers (Rodrigues et al., 2017). In addition, education of the public will be vital in the introduction and development of nanotechnology into the food production chain. Nanomaterials used in foods and food packaging should also ideally be reusable, recyclable, and/or biodegradable where possible (Rodrigues et al., 2017).

Nanoscale structures have shown unique functionalities that improve sensorial, physical, chemical, biological, antimicrobial, nutritional, and healthfulness properties of food products. As such the opportunities for the use of nanoparticles in the food production industry are far-reaching and more research in this space is warranted. As developments in the research and development of nanotechnologies continue, so will the opportunities for the poultry industry to benefit from nanoscience.

Acknowledgements

We are grateful for the financial support of the Rural Industries Research and Development Corporation (RIRDC).

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