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Viewpoint

Implications of nanotechnology for the agri-food industry: Opportunities, benefits and risks

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Nanotechnology has emerged as a technological advancement that could develop and transform the entire agri-food sector, with the potential to increase agricultural productivity, food security and economic growth for industries. Though as still a relatively new concept there are concerns over its safety, regulation and acceptance by the industry and consumers. This review set out to address the implications of nanotechnology for the agri-food industry by examining the potential benefits, risks and opportunities. Existing scientific gaps in knowledge are believed to be a prohibitive factor in addition to uncertainties in the level of awareness and attitudes towards the use of nanotechnology by the industry.

Introduction

Nanotechnology is a multidisciplinary field that covers a vast range of processes, materials, and applications encompassing physical, chemical, biological, engineering and electronic sciences. It focuses on the characterisation, fabrication and manipulation of substances at sizes in the nanoscale range, approximately between 1 and 100 nm. The smaller particle size, in combination with an increased surface area, exhibits unique and novel properties thus creating vast potential for applications (EFSA, 2009; Rashidi & Khosravi-Darani, 2011; Weiss, Takhistov, & McClements, 2006). A nanomaterial is defined as any material that has one or more dimensions in the nanoscale range, while a nanoparticle is a discrete entity that has all three dimensions in the nanoscale (Food and Agricultural Organisation of the United Nations (FAO)/World Health Organisation (WHO), 2010). Nanomaterials and nanoparticles can encompass the following nanoforms, which derive their names from their individual shapes and dimensions, *i.e.* nanotubes, nanofibres, nanorods, nanofilms, nanolayers, nanocoatings, nanosheets (Cushen, Kerry, Morris, Cruz-Romero, & Cummins, 2012).

Nanotechnology has already been used in construction materials for floors, walls, and machines, new devices and techniques in electronics, cosmetics, sporting equipment, wastewater treatment, medicine, and more recently in agriculture, and the food industry (Doyle, 2006). However, the implications of nanotechnology in the agri-food sector can be far reaching. Nanomaterials are naturally occurring in many plant and animal products, including the major constituents of milk (*i.e.* casein micelles, whey proteins, fat globules and lactose), as well as the fibrous structures in fish and meat, the crystalline structures in innate starches, and the molecular structure of cellulose fibrils in plant cells (Magnuson, Jonaitis, & Card, 2011; Morris, 2011). Engineered nanomaterials, for a variety of agri-food applications such as food additives, flavourings, novel foods, food packaging, feed additives and pesticides, are being developed. For food applications, nanotechnology can be applied by two different approaches, either from the "top-down" or by the "bottom up" (Ravichandran, 2010). The top down approach involves a physical or chemical process of breaking down larger particles of food matter into smaller particles of nanometres in dimension (Cushen *et al.*, 2012). Grinding or milling are examples of mechanisms used to produce such nanomaterials. Dry

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milling has been used for making high water-binding capacity wheat flour and has successfully been applied to green tea powder to enhance its antioxidant activity (Ravichandran, 2010). For green tea powder, this technique is used to reduce the powder size to 1000 nm, and so the high ratio of nutrient digestion and absorption leads to an increase in the activity of an oxygen-eliminating enzyme (Ravichandran, 2010). Homogenization is an alternative top down size reduction process which applies pressure to reduce the size of fat globules. This mechanism is used in the dairy industry worldwide to address milk separation and benefit consumers (Cushen *et al.*, 2012). By comparison, the bottom up approach involves manipulating individual atoms and molecules into nanostructures (Joseph and Morrison, 2006). Nanostructures are comprised of discrete functional parts, either inside or on the surface, of which one or more are in the nanoscale range (FAO/WHO, 2010). The bottom up approach can create more complex molecular structures of biological compounds. Methods applied in the bottom up approach include crystallisation, layer-by-layer deposition and self-assembly (Cushen *et al.*, 2012). For instance, the organisation of casein micelles or starch and the folding of globular proteins and protein aggregates are self-assembly structures which form stable entities (Ravichandran, 2010).

Nanotechnology has emerged as the technological advancement to develop and transform the entire agri-food sector, with the potential to increase global food production, in addition to the nutritional value, quality and safety of food (Mousavi & Rezaei, 2011). Applications may be classified as nano-inside (*i.e.* in the food product as in primary production or food processing) and nano-outside (*i.e.* food packaging) (Henchion *et al.*, 2013). Nanosensors and nano-based smart delivery systems are some of the applications of nanotechnology that are currently employed in the agricultural industry to aid with combating viruses and other crop pathogens, as well as to increase the efficiency of agrochemicals at lower dosage rates (Mousavi & Rezaei, 2011). Nanotechnology offers several perspectives for food applications due to the greater surface area of nanoparticles per mass unit making them more biologically active than larger sized particles. For instance, nanoparticles can be used as bioactive compounds in functional foods (Ezhilarasi, Karthik, Chhanwal, & Anandharamakrishnan, 2013). Bioactive compounds are health-promoting ingredients that can be found naturally in foods such as polyphenols, phytosterols, phytoestrogens, vitamins, minerals, fatty acids probiotics and prebiotics. These compounds exert physiological effects that might cause a risk reduction of certain chronic diseases linked to oxidative stress, such as cardiovascular disease and various forms of cancer (Chen, Remondetto, & Subirade, 2006). Nanosizing can greatly improve the properties of bioactive compounds such as delivery properties, solubility, targetability, and efficient absorption through cells, and prolonged compound residence times in the gastrointestinal tract (Ezhilarasi *et al.*, 2013). With regards to food packaging, nanotechnology can increase product shelf life by using packaging with antimicrobial properties to protect food against pathogens (Durán & Marcato, 2013). Within the food industry, nanotechnology has shown a wide range of novel applications including the use of nanoemulsions, nanocomposites, nanocarriers (nanocapsules) and nanofiltration, in addition to the development of smart packaging, nanosensors and nanobiosensors for quality control and food safety (Rashidi & Khosravi-Darani, 2011).

Application of nanotechnology in the agri-food sector is still a relatively new concept; the main reasons for its late incorporation are mainly due to issues relating to product labelling, potential consumer health risks, and a lack of unifying regulations and guidelines on nanotechnology governance (Coles & Frewer, 2013). Nevertheless, it is widely recognised by many countries worldwide that nanotechnology will bring significant benefits, and research in this area is attracting large scale investments by leading food companies, support from academic science, and increasing governmental financial investment and conceptual backing (FSAI, 2008; Gruère, 2012; Momin, Jayakumar, & Prajapati, 2013). According to the United States Department of Agriculture, nanotechnology's international market size is forecasted to be U.S. $1 trillion per year by 2015. The value of nanotechnology in the global food market is indicated to reach up to $3.2 billion USD by 2015 (Durán & Marcato, 2013).

The aim of this study is to review current and potential applications of nanotechnology in the agri-food industry, illustrating key benefits and opportunities for innovation but also considering the challenges ahead, including the potential risks of nanomaterials to human health and the environment and policy for regulatory issues. New food technologies, such as nanofood, can prove to be very sensitive issues with the public, and public perception can have a strong impact, both direct and indirect, on the progress of new technologies (Siegrist, 2010). A direct effect might be outright rejection whereas indirect effects could include the imposition of stricter regulations by governmental agencies perhaps leading to higher production costs. Consumer attitudes and risk perceptions regarding nanotechnology are however not addressed in this article. For reading in this area see Besley (2008); Cobb (2005); Fischer *et al.* (2013); Frewer *et al.* (2011); Greehy *et al.* (2013); Siegrist, 2010 amongst others.

Trends in nanotechnology and agri-food research

The concepts that started nanotechnology were first discussed in 1959 by the renowned physicist Richard Feynman in his talk *Theres Plenty of Room at the Bottom*, in which he described the possibility of synthesis via direct manipulation of atoms. The term "nanotechnology" was first used by Norio Taniguchi in 1974. Nanotechnology emerged as a field in the 1980s and from this time there has been an increase in scientific publications and awareness in the area