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REVIEW

Nanoscience and nanotechnologies in food industries: opportunities and research trends

Shivendu Ranjan · Nandita Dasgupta · Arkadyuti Roy Chakraborty · S. Melvin Samuel · Chidambaram Ramalingam · Rishi Shanker · Ashutosh Kumar

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Abstract Nanomaterials have gained importance in various fields of science, technology, medicine, colloid technologies, diagnostics, drug delivery, personal care applications and others due to their small size and unique physico-chemical characteristic. Apart from above mentioned area, it is also extensively being used in food sector specifically in preservation and packaging. The future applications in food can also be extended to improve the shelf life, food quality, safety, fortification and biosensors for contaminated or spoiled food or food packaging. Different types and shapes of nanomaterials are being employed depending upon the need and nature of the food. Characterisation of these nanomaterials is essential to understand the interaction with the food matrix and also with biological compartment. This review is focused on application of nanotechnology in food industries. It also gives insight on commercial products in market with usage of nanomaterials, current research and future aspects in these areas. Currently, they are being incorporated into commercial products at a faster rate than the development of knowledge and regulations to mitigate potential health and environmental impacts associated with their manufacturing, application and disposal. As nanomaterials are finding new application every day, care should be taken about their potential toxic effects.

Keywords Nanotechnology · Nano-food · Functional food · Food packaging · Nano-food technology

Shivendu Ranjan and Nandita Dasgupta have contributed equally.

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Introduction

The term 'nano' is coined from the Greek word for dwarf. A nanometre (nm) is one-billionth of a metre, or approximately one hundred thousandth of the width of a human hair. Nanotechnology has many applications tissue engineering, drug delivery, biomedical engineering etc. (Danie et al. 2013). Nanotechnology is also administered into the 'food sector' which includes nanosensors, tracking devices, targeted delivery of required components, food safety, new product developments, precision processing, smart packaging etc. (Huang et al. 2010; McClements et al. 2009). Natural protein, carbohydrate and fat molecules have been modified with nanotechnology and the modified

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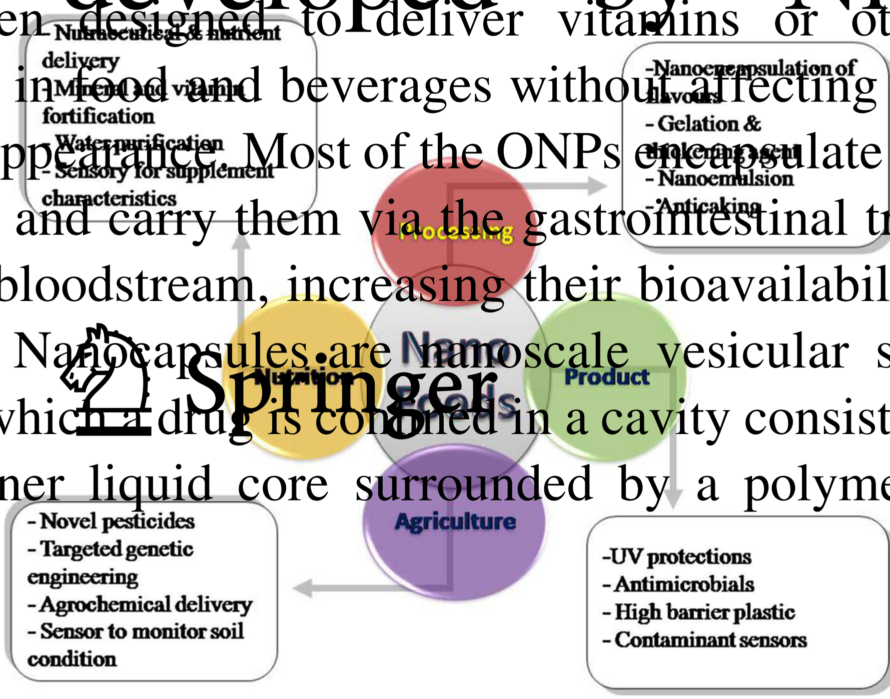

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et al. 2004). NEs are much more thermodynamically stable compared to conventional emulsions under a range of different conditions. This stability stems from their smaller size (typically 50–500 nm compared to 1,200 nm) and monodispersivity implying that they can be diluted without changing the droplet size distribution. The specific usage of any surfactant in the formulation is critical to the stability of the final emulsion. NEs can be used to encapsulate functional food components at oil/water interfaces or throughout the continuous phase of the system (Weiss et al. 2008).

Production of NE

NE can be produced using a variety of methods, which are classified as either high-energy or low-energy approaches. High-energy approach for NEs preparation can further be classified into high-pressure homogenisation (Quintanilla-Carvajal et al. 2010), ultrasound method (Sanguansri and Augustin 2006) and high-speed devices method (Anton et al. 2008). Similarly, low energy approaches are further classified into membrane emulsification (Sanguansri and Augustin 2006), spontaneous emulsification (Anton et al. 2008), solvent displacement (Yin et al. 2009), emulsion inversion point (Sadtler et al. 2010) and phase inversion point (Sadurní et al. 2005).

Industrial products of NEs in food markets

NE production for encapsulation and delivery of functional compounds is one of the major fields of nanotechnology applied to food industry. Applications of this technology is described in examples are given below.

NutraLease, a technology start-up company by a scientific team is working to improve the bioavailability of functional compounds. Some functional compounds like lutein, lycopene, β-carotene, vitamins A, D3 and E, Q10, phytosterols, and lastly isoflavones are available contained in beverages. Their technology is derived from self-assembled (implying low energy approach) NEs which then achieves a better encapsulation rate as well as an improved bioavailability in the human body (Halliday 2007; Silva et al. 2012). NutraLease NEs can protect flavour compounds from manufacturing condi-tions and this continues all through the beverages' shelf life. It is claimed that NEs can capture the flavour and protect it from temperature, oxidation, enzymatic reactions and hydrolysis and are thermodynamically stable at a wide range of pH values (Silva et al. 2012). The product brand name is nano-self-assembled structured liquids (NSSL) under the category of genetic food additive which contains nano-micelles for encapsulation of nutraceuticals. NSSL is used for improved bioavailability means nutraceuticals are released into membrane between the digestive system and the blood.

Aquanova has developed a nanotechnology-based carrier system using 30 nm micelles to encapsulate active ingredients such as Vitamins C and E and fatty acids which can be used as preservatives and aids (Aquanova undated). Aquanova markets its micelles as ''NovaSol'' and claims that the nanoscale carrier system increases the potency and bioavailability of active ingredients. Aquanova in collaboration with Zyme are offering omega 3 in 30–40 nm size range nano-capsules which is 4,000 times smaller to the existing product in market (Silva et al. 2012; H a l l i d a y 2007). NovaSol portfolio is divided into two categories: healthy func-tional compounds (coenzyme Q10, DL-α-tocopherol acetate, vitamins A, D, D3, E, and K and omega three fatty acids) and natural colourants (β-carotene, apoca-rotenal, chlorophyll, curcumin, lutein and sweet pepper extract) (Silva et al. 2012). Novasol has been used as an optimum carrier system of hydrophobic substances for a higher and faster intestinal and dermal resorption and penetration of active ingredients. Aquanova claims enhanced stability (both in terms of pH and tempera-ture) of encapsulated functional compounds and stand-ardised additive concentrations (Silva et al. 2012).

Unilever has made ice cream healthier without compromising on taste through the application of NEs. The objective is to produce ice cream with lower fat content, achieving a fat reduction from the actual 16–1 % (Silva et al. 2012).

Other applications of NEs into the food industry include antimicrobial NEs for decontamination of food equipment, packaging or food (Center for Biological Nanotechnology 2001; Gruère et al. 2011).

Nanotechnology and research trends in food packaging

Food industries are always searching for new cheaper methods to produce and to preserve food and with this need we enter into the realm of nanotechnology. Recent trends in food packaging related with forms are being used in food packaging and food ingredients i.e. food additives, nutraceuticals etc. (Chen et al. 2006) but over the long term, facts can be brought upon controlled release of nano-encapsulated food ingredients or nutrients (Morris 2006). Nanotechnology can also improve the water disperse ability, thermal stability and oral bioavailability of the functional compounds of food (Huang et al. 2010; McClements et al. 2009).

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S. no.	Major field of research	Details of research	References
		Natural dipeptide antioxidants, e.g. L-carnosine have potential application as biopreservatives in food technology. However, with food they have proteolytic degradation and a potential interaction of peptide with food components. Hence they can be used in encapsulated form	Maherani et al. (2012)
		Bio Delivery Sciences International has developed Bioral™ nanocochleate nutrient delivery system, which is a phosphatidyl serine carrier (~50 nm), derived from soya bean (GRAS status). This system has been used for protecting micronutrients and antioxidants from degradation during manufacture and storage	Chaudhry and Groves (2010)
		Fat-soluble/water-soluble nanostructured food ingredients (e.g. carotenoids, phytosterols, and antioxidants) to be dispersed in water or fruit drinks to increase the bioavailability, taste, colour, etc	Chen et al. (2006)
		Synthetic form of tomato carotenoid, lycopene (particle size of 100 nm, from BASF's US patent US5968251), has been developed and accepted as GRAS substance by the Food and Drug Administration (FDA). It can be added to soft drinks to provide colour and health benefits, also synthetic lycopene in association with vitamin E can inhibit the growth of prostate cancer in nude mice. Lycopene has been included in other products such as baking mixtures and blancmanges	Chaudhry and Groves (2010), Limpens et al. (2006)
		Nanostructured antioxidant agent coenzyme Q10 (CoQ10) can be added to food and used as a first line therapeutic agent for prophylaxis	Ankola et al. (2007)
		Entrapment of essential oils within zein nanostructure allows their dispersion in water, enhancing their potential for use as antioxidant and antimicrobial in food preservation and control of human pathogenic bacterium, *Escherichia coli*	Wu et al. (2012)
		Catechins (natural health care product, an antioxidant). However, the oral bioavailability of tea catechins is known to be very low, so, self-assembled nanostructures composed of chitosan and an edible polypeptide, poly(g-glutamic acid) was designed, for oral delivery of tea catechins, which can be used as food additives for drinks, foods and dietary supplements	Zhang et al. (2004), Green et al. (2007), Tang et al. (2013)

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		Solid lipid NPs are valuable as an oral delivery carrier to enhance the gastrointestinal absorption and, thus, the bioavailability of quercetin, a natural healthcare product	Li et al. (2008b)
		Nanotea, from Chinese industry is a nano-selenium-enriched tea, which is claimed to enhance selenium uptake and bioavailability	Chaudhry et al. (2008)
		Novasol® from Aquanova® AG (Darmstadt, Germany) is a nano-micelle based carrier system for use in food and beverage. Such system can encapsulate a variety of functional food ingredients (e.g. benzoic acid, citric acid, vitamins A and E, soya bean isoflavones, β-carotene, lutein, ω-3 fatty acids, CoQ10). An increase in bioactive bioavailability with Novasol® has also been claimed	Carla et al. (2013), Bugusu et al. (2011)
		Nutralease®, developed by the scientists of the Hebrew University of Jerusalem, Israel, is a technology used to improve functional food ingredient solubility and bioavailability	Carla et al. (2013)
		It is a nanosized self-assembled liquid structure that can carry different nutraceuticals such as coenzyme Q10, lutein, lycopene, vitamins or phytosterols	
		Shemen Industries Ltd. (Haifa, Israel) developed 'canola active oil' fortified with supplements (e.g. phytosterols).	Bugusu et al. (2011)
		Nutri-Nano™ CoQ-10 Solgar (Leonia, NJ, USA), a commercial product which enhances the absorption of fat-soluble nutrients through their conversion into water-soluble ones	Carla et al. (2013), Bugusu et al. (2011)
		NEs in food products are as 'creamy' as conventional food products, without compromising the mouth feel and flavour, being an alternative to full-fat food products. As the size of the droplets in an emulsion is reduced, it is less likely that the emulsion will break down and separate and may reduce the need for certain stabilizers, e.g. low-fat nanostructured mayonnaise, spreads and ice creams	Chaudhry et al. (2008), Carla et al. (2013)
		Nanostructured delivery system have been used to mask the undesirable taste and odour of tuna fish oil added to bread for health benefits and the addition of live probiotic microbes to promote gut functions	Cushen et al. (2012)
		Nanostructured liposome has been used in the entrapment of proteolytic enzymes for cheese production, reducing the production time to half without losing flavour and texture properties	Mozafari et al. (2006), Walde and Ichikawa (2001)

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Various applications of nanoparticles in the food industries are globally focused on (i) sensory improvements (flavour/colour enhancement, texture modification), (ii) increased absorption and targeted delivery of nutrients and bioactive compounds, (iii) stabilization of active ingredients such as nutraceuticals in food structures, (iv) packaging and product innovation to increase shelf life, (v) sensors to assess the safety of food, (vi) as an antimicrobial against the food born pathogenic bacteria (Fig. 1). Nanomaterials (NMs) are used in several downstream processes to get the better results, e.g. the extraction of a relatively large molecular weight protein, bovine serum albumin. Using the nano-sized reverse micelles of nonionic surfactant polyoxyethylene p-t-octylphenol (Triton-X-100), Hebbar and Raghavarao (2007) showed that nano-sized AOT/toluene reverse micellar system resulted in complete forward and back extraction without affecting the protein structure. Addition of Triton-X-100 to AOT decreased the extraction efficiency as compared to AOT alone, which may be attributed to the reduced hydrophobic interaction. The stability of NMs in food is dependent on a range of storage conditions (low and high temperature). This may affect both the Nanoparticle (NP) stability within the food as well it can change the properties of the biomolecules in food and potential interactions with the NPs (Morris 2006). The application of nanotechnology to the food sector may allow the modification of many macroscale characteristics of food, such as texture, taste, other sensory attributes, coloring strength, processability and stability during shelf life which helps to increase the shelf life of food (Huang et al. 2010; McClements et al. 2009).

Nanostructured materials exhibit unique physicochemical properties that open windows of opportunity for the creation of new high performance materials, which will have a critical impact on food manufacturing, packaging and storage. Currently, the application nanotechnology in food production chain is focused on the development of nanosized food ingredients and additives, delivery systems for bioactive compounds and innovative food packaging. Additionally the applications such as a nanocoating that protects tomatoes from humidity and oxygen,

Fig. 1 Pictorial representation for some of the major applications of nanotechnology in different sectors of food and agriculture

their ability to carry different reactions with different ingredients and environmental conditions. Depending on the chemical characteristics, NPs can be divided into two broad categories: organic and inorganic.

Organic nanoparticle (ONP)

Sometimes referred to as nanocapsules, when used as vehicles for delivery of essential nutrients or pharmaceuticals. There are six classical methods for the preparation of nanocapsules: nanoprecipitation, emulsion-diffusion, double emulsification, emulsion-coacervation, polymer-coating and layer-by-layer (Mora-Huertas et al. 2010). They are likely to be used to enhance the nutrient value of food systems through improvement or alteration of food functionality. ONP have been designed to deliver vitamins or other nutrients in food and beverages without affecting the taste or appearance. Most of the ONPs encapsulate the nutrients and carry them via the gastrointestinal tract into the bloodstream, increasing their bioavailability. ONP or Nanocapsules are nanoscale vesicular systems in which a drug is confined in a cavity consisting of an inner liquid core surrounded by a polymeric

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