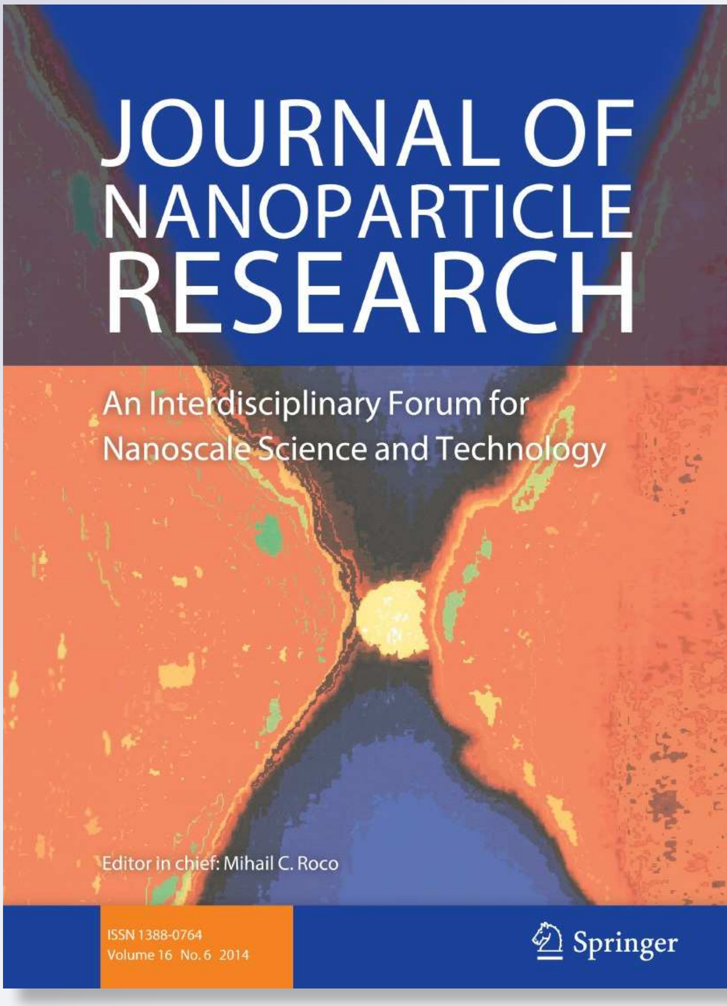
Nanoscience and nanotechnologies in food industries: opportunities and research trends

Shivendu Ranjan, Nandita Dasgupta, Arkadyuti Roy Chakraborty, S. Melvin Samuel, Chidambaram Ramalingam, Rishi Shanker, et al.

Journal of Nanoparticle Research
An Interdisciplinary Forum for
Nanoscale Science and Technology

ISSN 1388-0764
Volume 16
Number 6

J Nanopart Res (2014) 16:1-23
DOI 10.1007/s11051-014-2464-5



Springer

J Nanopart Res (2014) 16:2464
DOI 10.1007/s11051-014-2464-5

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

Received: 24 February 2014 / Accepted: 14 May 2014 / Published online: 29 May 2014

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

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

Shivendu Ranjan and Nandita Dasgupta have contributed equally.

S. Ranjan · N. Dasgupta · A. R. Chakraborty · S. Melvin Samuel · C. Ramalingam (✉)
Instrumental and Food Analysis Laboratory, Industrial Biotechnology Division, School of Bio Sciences and Technology, VIT University, Vellore, Tamil Nadu, India
e-mail: cramalingam@vit.ac.in; foodlabsbst@gmail.com

R. Shanker · A. Kumar
Institute of Life Sciences, School of Science and Technology, Ahemdabad University, Ahemdabad, Gujrat, India

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 focus 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).

Various applications of nanoparticles in the food industries are globally focused in (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, colouring strength, processability and stability during shelf life which help to increase physiochemistry 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 nano-sized 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,

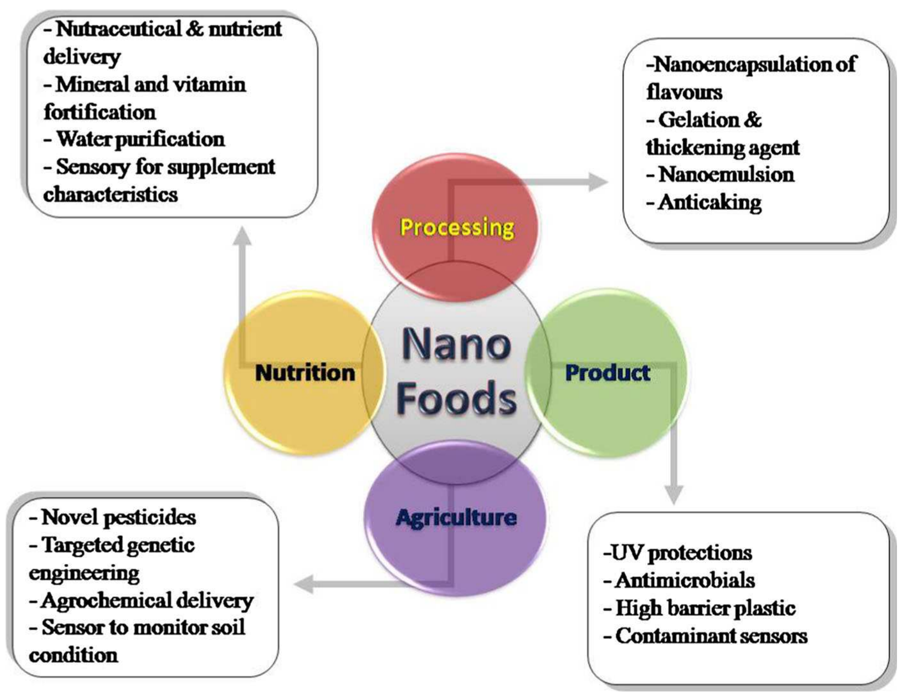


Fig. 1 Pictorial representation for some of the major applications of nanotechnology in different sectors of food and agriculture

bread containing nanocapsules of omega-3 fatty acids and a juice containing vitamin A encapsulated in starch, use of nanocans for packaging and transportation of liquid beverages because of their light weight are gaining importance in the consumer. Also, the use of NPs in food packaging provides additional mechanical, thermal, chemical and microbial, fungal resistance properties, together with the additional feature such as microbiological and biochemical change sensing, colour-based sensor strip to monitor the freshness of the food. These applications of NPs and nanotechnologies boost the researchers and the industry for the application of this technology.

Classification of NMs

NMs are generally classified as: (i) nanoparticles (NPs), (ii) nanoclays (NCs) and (iii) nanoemulsions (NEs) which can be synthesised by a number of methods and have many applications in food sector.

Nanoparticles

NPs can be categorized into different types based on 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 membrane (Quintanar et al. 1998). However, seen from a general point of view, they can be defined as nano-vesicular systems that exhibit a typical core-shell structure in which the drug is confined to a reservoir or within a cavity surrounded by a polymer membrane or coating (Anton et al. 2008). The cavity can contain the active substance in liquid or solid form or as a molecular dispersion (Radtchenko et al. 2002). Nanocapsules have countless uses, which include medical promising applications for drug delivery, food enhancement, nutraceuticals and for the self-healing of materials. The benefits of encapsulation methods are to protect the hidden agent in the adverse environment, for controlled release and for precision targeting (Ezhilarasi et al. 2012).

Inorganic nanoparticles (INP)

Similar to organic, INP are also having several methods of production, e.g. gas phase INP synthesis method and liquid phase INP synthesis method which are further classified into different methods. Gas phase INP synthesis methods has mainly three types for INP synthesis which are named as flamed spray synthesis (Stark and Pratsinis 2002; Maciejewski et al. 2008), laser-induced gas evaporation synthesis (Ullmann et al. 2002) and plasma-based synthesis (Kinemuchi et al. 2003). Liquid phase INP synthesis methods may further categorized into co-precipitation method (Cushing et al. 2004) and sol–gel approach (Hench and West 1990).

Inorganic ingredients manufactured at the nanoscale with variations of compounds and approved for use in food, e.g. titanium dioxide, a food colourant, can be used as a UV protection barrier in food packaging when used as a NP. New storage containers/utensils (food contact materials) based on embedded INP have been designed for preservation of prepared foods. The most common application is the use of silver NP (Ag NP) as an antimicrobial agent. Applications for Ag NP include use in fridge panels, storage boxes, packaging lines and other surfaces which come into contact with food during manufacture. Ag NP have also been added to contact areas such as floor tiles to reduce the bacterial load in the surrounding manufacturing environment. Food storage bins are being produced with Ag NP embedded in the plastic for killing bacteria from any food that was previously stored in the bins and minimising health risks.

Inorganic nanoceramic (solid pellet INP) has been added to oil cooking systems in restaurants in the USA to extend the life of chip oil whilst giving a crisper food. The technology is based on the ability of the NP to act as a catalyst, limiting thermal polymerisation process in the oil resulting in a crisper deep-fried food and longer shelf life for the oil (Food Safety Authority of Ireland 2008).

Nanoclays (NCs)

They are naturally occurring aluminium silicate, primarily composed of fine-grained minerals having sheet-like geometry. The sheet-structured hydrous silicates are generally referred to as phyllosilicates. They are inexpensive and eco-friendly materials and have been found for multifarious application. These clay minerals have been widely studied in practical applications such as in geology, agriculture, construction, engineering, process industries and environmental applications. They provide an attractive alternative for the decontamination of soils, underground waters, sediments and industrial effluents (Garrido-Ramirez et al. 2010). They are also widely used materials in drug products like as excipients and active agents (Carretero and Pozo 2009).The most studied NC is montmorillonite (MMT), whose chemical general formula is $Mx(Al_4–xMgx)\ Si_8O_{20}(OH)_4$. MMT is a representative of 2:1 layered *phyllosilicates*, whose platelets have two layers of tetrahedral silica sheets filled with a central octahedral alumina sheet (Weiss et al. 2006). This kind of clay has a moderate negative surface charge that is important to define the interlayer spacing (Alexandre and Dubois 2000). The imbalance of the surface negative charges is compensated by exchangeable cations (typically Na^+ and Ca^{2+}).The parallel layers are linked together by weak electrostatic forces (Tan et al. 2008). MMT is excellent reinforcing filler, due to its high surface area and large aspect ratio, which ranges from 50 to 1,000 (Uyama et al. 2003).The improved barrier properties of polymer-clay nanocomposites (PCNs) seem to be due to an increased tortuosity of the diffusive path for permeants, forcing them to travel a longer path to diffuse through the film. The increase in path length is a function of the aspect ratio of the clay and the volume fraction of the filler in the composite. This theory was developed by Nielsen (1967) and was further corroborated by other authors (Adame and Beall 2009).Clays have been also reported to improve the mechanical strength of biopolymers (Chen and Evans 2005; Cyras et al. 2008), although they may decrease polymer elongation (Petersson and Oksman 2006).

Industrial products of NC

There are several NC products in the market, e.g. Imperm, Aegis, Durethan etc. Imperm (from Nanocor Inc.) is used in multi-layer polyethylene bottles and sheets for food and beverage packaging to minimise the loss of CO_2 from the drink and the ingress of O_2 into the bottle, thus keeping beverages fresher and extending shelf life. Aegis_OX (Honeywell Inc.) polymerised nanocomposite film is an oxygen-scavenging barrier resin formulated for use in co-injection polyethylene bottle applications, e.g. beer, fruit juice and soft drinks. These resins are a blend of active and passive nylon using O_2 scavengers and passive nanocomposite clay particles to enhance the barrier properties for retaining CO_2 and keeping O_2 out. Durethan_KU2-2601 (Bayer AG) is a new hybrid plastic, which comprises polyamide (PA) and layered silicate barriers. The plastic incorporates Nanocor's clay to produce a film with increased barrier properties, enhanced gloss and stiffness. It is intended for the use in applications where conventional PA is more permeable and too expensive, e.g. paperboard juice containers. Nanoclays are naturally occurring aluminium silicates which are primarily composed of fine-grained minerals with a fixed natural structure in sheet-like geometry (Joseph and Morrison 2006).

Nanoemulsions (NEs)

Nanoemulsion (NE) consists of a lipid phase dispersed in an aqueous continuous phase, with each oil droplet being surrounded by a thin interfacial layer consisting of emulsifier molecules (Acosta 2009; Tadros et al. 2004). Usually, NEs are highly stable to gravitational separation because the relatively small particle size means that Brownian motion effects dominate gravitational forces. They also have good stability against droplet aggregation because the range of attractive forces acting between the droplets decreases with decreasing particle size, whilst the range of steric repulsion is less dependent on particle size (Tadros 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 conditions 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; Halliday 2007). NovaSol portfolio is divided into two categories: healthy functional compounds (coenzyme Q10, DL-α-tocopherol acetate, vitamins A, D, D3, E, and K and omega three fatty acids) and natural colourants (β-carotene, apocarotenal, 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 temperature) of encapsulated functional compounds and standardised 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

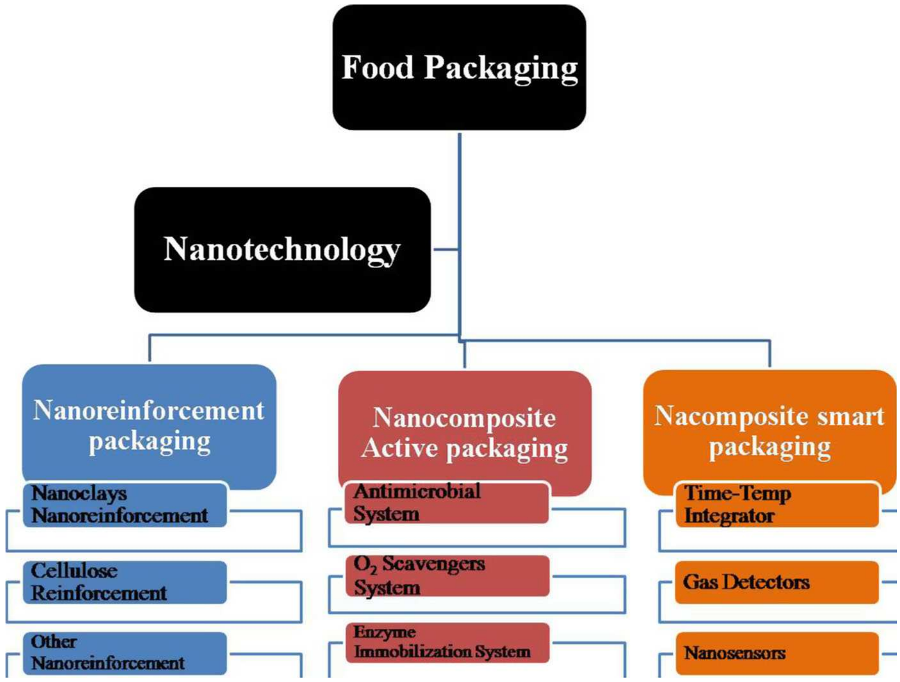


Fig. 2 The research trends of food packaging with the help of nanotechnology

nanoreinforcement, nanocomposite active packaging and nanocomposite smart packaging (Fig. 2). Nanoreinforcement is mainly used to give extra tensile strength of food packets by different reinforcement method using nanoclays, cellulose etc. Nanocomposite active packaging is the integration of many useful systems along with the food packets, e.g. antimicrobial, oxygen scavenging and enzyme immobilization system. Similarly, nanocomposite smart packaging mainly involves sensors, e.g. time–temperature integrator (TTI), gas detectors and other nanosensors.

Nanoreinforcements in food packaging materials

Polymers have replaced conventional materials (glass, ceramics, metals, paper and board) in food packaging owing to their functionality, light weight, low cost and ease of processability. However, their strength and capability to resist deformation are lower as compared to metals and ceramics (Jordan et al. 2005). Furthermore, their inherent permeability to gases and vapours is another limiting property in food packaging (Arora and Padua 2010). Nanoreinforcement techniques are used to increase viability and tensile strength of packaging materials by filling the gaps of it. Polymer nanocomposites usually have a much better polymer/filler interactions than the usual composites (Ludueña et al. 2007).

Nano-fillers have a vital role to enhance composite performance by improving their properties such as mechanical strength, thermal stability and barrier properties. The characteristic parameters that contribute greatly in modifying the properties of various composites are the filler loading; their size and shape; and their affinity towards matrix material. Nanoclay-filled polymer matrix-based nanocomposites have generated a significant amount of attention within the materials industry for their enhanced performance. This area emerged with the recognition that exfoliated clays could exhibit superior strength, modulus and higher barrier properties in comparison to virgin polymer matrix (Goettler et al. 2007). With the recent advancement in nanotechnology, the correlation of material properties with filler size has become a point of great interest. NPs have attracted a great deal of interest owing to their extraordinary potential to exhibit novel characteristics that cannot be achieved with their traditional micro-scale counter parts. There have been various studies on the incorporation of different NPs into the matrix (Kriegel et al. 2008), however, the packaging industry has recently focused its attention mainly on nanoclay particulates due to their easy availability, low cost, easy processability and good performance. Carbon-based materials like carbon nanotubes and graphene nanosheets are also being developed (Arora and Padua 2010).

A uniform distribution of nanofillers into a polymer matrix results in a very large matrix/filler interfacial area, which restricts the mechanical mobility of the matrix, and improves its mechanical, thermal (especially glass transition temperature—T_g) and barrier properties. Fillers with higher aspect ratios have higher specific surface area, providing better reinforcing effects (Dalmas et al. 2007). The aspect ratio is defined by the ratio of the largest to the smallest dimension of filler. Further an interphase region of decreased mobility surrounding each nanofiller result in a percolating interphase network in the composite which plays an important role in improving the nanocomposite properties (Qiao and Brinson 2009). For constant filler content, a reduction in particle size increases the number of filler particles, bringing them closer to one another; thus, the interface layers from adjacent particles overlap, altering the bulk properties more significantly (Jordan et al. 2005).

Nanoclays reinforcement

In last two decades, a new and an emerging class of clay filled polymers, called PCNs, has been developed and much research activity has been dedicated to the development of PCNs that could improve the performances of polymers for food packaging by adding NPs. In contrast with the typical tactoid structure of microcomposites (conventional composites), in which the polymer and the clay tactoids remain immiscible (Ludueña et al. 2007; Alexandre et al. 2009), the interaction between layered silicates and polymers may produce two types of nanoscale composites (Fig. 3), namely: intercalated nanocomposites, which result from penetration of polymer chains into the interlayer region of the clay, producing an ordered multilayer structure with alternating polymer/inorganic layers (Weiss et al. 2006), and exfoliated nanocomposites, which involve extensive polymer penetration, with the clay layers delaminated and randomly dispersed in the polymer matrix (Ludueña et al. 2007).

Cellulose nanoreinforcements

Cellulose nanoreinforcements (CNRs) are interesting materials for the preparation of low cost, lightweight and high-strength nanocomposites (Podsiadlo et al. 2005). Cellulose chains are synthesised in living organisms (mainly plants) as microfibrils (or nanofibers), which are bundles of elongated molecules (with 2–20 nm in diameter and micrometric in length) stabilized by hydrogen bonds (Mattoso et al. 2009).

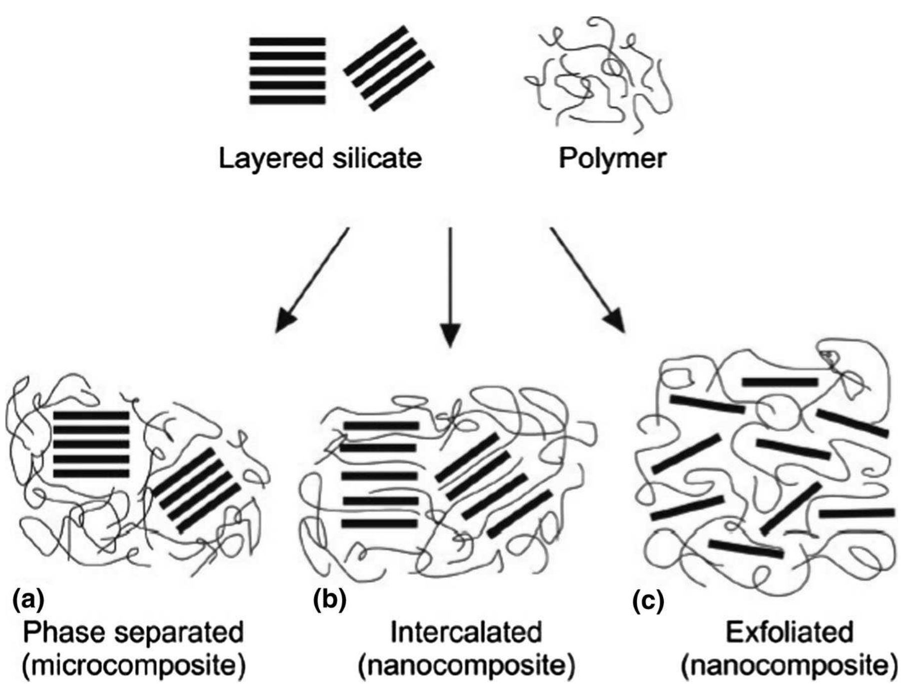


Fig. 3 Types of nanocomposites (courtesy of Alexandre et al. 2009)

Each microfibril, formed by elementary fibrils, has crystalline and amorphous regions. The crystalline parts, which may be isolated by procedures such as acid hydrolysis, are the nanocrystals or nanowhiskers whose aspect ratios are related to the origin of the cellulose and processing conditions (Azizi et al. 2005).

Several other studies have reported positive effects of CNRs on tensile properties—especially on modulus—of polymers, although they tend to decrease elongation. According to Helbert et al. (1996), the great effect of CNRs on modulus is ascribed not only to the geometry and stiffness of the fillers, but also to the formation of a fibrillar network within the polymer matrix, the CNRs being probably linked through hydrogen bonds. Similar to nanoclays, the presence of CNRs is believed to increase the tortuosity of the diffusivity path for the permeants, lowering the polymer permeability (Sanchez-Garcia et al. 2008). In fact, several studies have reported improvements in barrier properties of polymers by addition of CNRs. The barrier properties are further enhanced if the filler is less permeable, well dispersed in the matrix and with a high aspect ratio (Lagaron et al. 2004).

Other nanoreinforcements

Carbon nanotubes may consist of a one-atom thick single-wall nanotube, or a number of concentric tubes called multiwalled nanotubes, having extraordinarily high aspect ratios and elastic modulus (Zhou et al. 2004). Several polymers have been found to have their tensile strength/modulus improved by addition of carbon nanotubes, such as polyethylene naphtalate (Kim et al. 2008), polyvinyl alcohol (Chen and Evans 2005), polypropylene (Prashantha et al. 2009) and a PA (Zeng et al. 2006). Silica NPs (nSiO$_2$) have been reported to improve tensile properties of polypropylene (Vladimiriov et al. 2006), starch (Xiong et al. 2008), starch/polyvinyl alcohol (Tang and Liu 2008), decreasing water absorption by starch (Tang and Liu 2008; Xiong et al. 2008) and improving oxygen barrier of polypropylene (Vladimiriov et al. 2006). Jia et al. (2007) prepared nanocomposites of polyvinyl alcohol with nSiO$_2$ by radical copolymerisation of vinyl silica NPs and vinyl acetate. The nanocomposites had improved thermal and mechanical properties when compared to the pure polyvinyl alcohol, due to strong interactions between nSiO$_2$ and the polymer matrix via covalent bonding.

Nanocomposite active food packaging

An active food packaging unlike conventional food packaging may be defined as a system that not only acts as a passive barrier but also interacts with the food in some desirable way, e.g. by releasing desirable compounds (antimicrobial or antioxidant agents, for instance), or by removing some detrimental factor (such as oxygen or water vapour). The consequences of such interactions are usually related to improvements in food stability. Some of the main examples of food packaging systems are given in the below sections.

Antimicrobial systems

Antimicrobial systems are fast emerging as viable solutions due to their help in controlling the growth of pathogenic and spoilage causing organisms on food surfaces where microbial growth takes place predominantly. Further interest is drawn by the use of nanocomposites in these systems due to naturally different properties at the nanoscale range when compared to microscalar range. This can be highlighted by the higher surface to volume ratio of nanoscale materials in relation to microscale products. Such properties enable nanomaterials to attach more copies of microbial molecules and cells (Luo and Stutzenberger 2008). Nanoscale materials have been investigated for antimicrobial activity as growth inhibitors (Cioffi et al. 2005), killing agents (Huang et al. 2005; Kumar and Münstedt 2005) or antibiotic carriers (Gu et al. 2003).

Silver apart from its known toxicity towards a variety of microorganisms (Liau et al. 1997) also offers some other advantages such as higher temperature stability and low volatility (Kumar and Münstedt 2005). A larger surface area advocates for a greater interaction with microbial cells (Kvítek et al. 2008) and this is shown by greater effectiveness of silver NPs when compared to the proven antimicrobial activity (Yu et al. 2007; Tankhiwale and Bajpai 2009) of larger silver particles. Silver is found as a commonly used basis for nanocomposite formation due to described mechanisms of its antimicrobial activity namely: (a) adhesion to the cell surface, degradation of lipopolysaccharides and formation of 'pits' in the membranes, largely increasing permeability (Sondi and Salopek-Sondi 2004); (b) penetration inside bacterial cell, damaging DNA (Li et al. 2008a) and (c) releasing antimicrobial Ag^+ ions by dissolution of silver nanoparticles (Morones et al. 2005). The works of Morones et al. 2005 is consistent with the findings of Kumar and Münstedt 2005; and this leads us to believe that released Ag^+ ions bind to electron donor groups in biological groups containing sulphur, oxygen or nitrogen. Silver NPs have also been reported to absorb and decompose ethylene, which may contribute to their effects on extending shelf life of fruits and vegetables (Li et al. 2009).

Nanostructured calcium silicate (NCS) was used by Johnston (2010) to adsorb Ag^+ ions from a solution. The resulting NCS–Ag complex exhibited effective antimicrobial activity at desirably low levels of silver down to 10 mg/kg, and was feasible for incorporation into food packaging as an antimicrobial agent. Titanium dioxide (TiO_2) is widely used as a photocatalytic disinfecting material for surface coatings (Fujishima et al. 2000). TiO_2 photocatalysis, which promotes peroxidation of the phospholipids present in microbial cell membranes (Maness et al. 1999), has been used to inactivate food-related pathogenic bacteria (Robertson et al. 2005). Chawengkijwanich and Hayata (2008) developed a TiO_2 powder-coated packaging film able to reduce *E. coli* contamination on food surfaces. Gelover et al. (2006) demonstrated the efficacy of TiO_2-coated films exposed to sunlight to inactivate faecal coliforms in water. Metal doping improves visible light absorbance of TiO_2 (Anpo et al. 2001), and increases its photocatalytic activity under UV irradiation (Choi et al. 1994). It has been demonstrated that doping TiO_2 with silver greatly improved photocatalytic bacterial inactivation (Reddy et al. 2007). This combination was explored by Cheng et al. (2006), who have obtained effective antibacterial activity from a polyvinyl chloride nanocomposite with TiO_2/Ag^+NPs. Qi et al. (2004) have reported antibacterial activity from chitosan NP, which may be due to interactions between the positively charged chitosan and the negatively charged cell membranes thereby increasing membrane permeability and eventually causing rupture and leakage of the intracellular material. This is consistent with the observation by the same authors (Qi et al. 2004) that both chitosan and its engineered NPs are ineffective at pH lower than 6, which is probably due to the absence of protonated amino groups.

Another two antimicrobial mechanisms were proposed by Rabea et al. (2003), namely: chelation of trace metals by chitosan, inhibiting microbial enzyme activities; and (in fungal cells) penetration through the cell wall and membranes to bind DNA and inhibit RNA synthesis. Carbon nanotubes have also been reported to have antibacterial properties. Direct contact with aggregates of carbon nanotubes have been demonstrated to kill *E. coli*, possibly because the long and thin nanotubes puncture microbial cells, causing irreversible damages and leakage of intracellular material (Kang et al. 2007). On the other hand, there are studies suggesting that carbon nanotubes may also be cytotoxic to human cells, at least when in contact to skin (Monteiro-Riviere et al. 2005) or lungs (Warheit et al. 2004). Once present in the food packaging material, the nanotubes might eventually migrate into food. Thus, it is mandatory to know any eventual health effects of ingested carbon nanotubes.

O_2 scavengers

Oxygen (O_2) participates in several forms of food deterioration. Direct oxidation reactions result in browning reactions and rancid flavours, to name only a few examples. Food deterioration by indirect action of O_2 includes food spoilage by aerobic microorganisms. The incorporation of O_2 scavengers into food packaging systems can maintain very low O_2 levels, which is useful for several applications. Oxygen scavenger films were successfully developed by Xiao-e et al. (2004) by adding TiO_2 NPs to different polymers. The nanocomposite materials could be used as packaging films for a variety of oxygen-sensitive food products. Since TiO_2 acts by a photocatalytic mechanism, its major drawback would be the requirement of UVA light (Mills et al. 2006).

Enzyme immobilization systems

Enzymes have a variety of applications in food industry. However, their sensitivity to processing conditions and/or to enzyme inhibitors can sometimes restrict the applicability of the direct enzyme addition to foods. Immobilization is usually an effective way to improve enzyme stability to pH and temperature, resistance to proteases and other denaturing compounds, as well as to provide an adequate environment for their repeated use or controlled release (Lopez-Rubio et al. 2006). Enzyme immobilization has been considered for packaging applications (Soares and

Hotchkiss 1998). The incorporation of enzymes like lactase or cholesterol reductase to packaging materials could increase the value of food products and answer the needs of consumers with enzyme deficiencies (Fernández et al. 2008). Nanoscale enzyme immobilization systems would have enhanced performance when compared to conventional ones, because of their much higher surface contact area and mass transfer rate, which are probably the most important factors affecting the effectiveness of such systems (Fernández et al. 2008). Approaches might be expected dealing with enzyme adsorption into nanoclays incorporated to polymers (Rhim and Ng 2007), since NCs have a high affinity for protein adsorption, and have been reported to be efficient enzyme carriers (Gopinath and Sugunan 2007). Conductive polymers may also be used as immobilizing matrices for biomolecules (Ahuja et al. 2007), as reported by Sharma et al. (2004), who immobilized glucose oxidase onto films of poly(aniline-co-fluoroaniline). SiO_2 nanoparticles have been modified to immobilize glutamate dehydrogenase and lactate dehydrogenase (Qhobosheane et al. 2001), which have shown excellent enzyme activity upon immobilized.

Nanocomposite smart packaging systems

A 'smart' food packaging system may be defined as a system that 'perceives' some property of the packaged food and uses a variety of mechanisms to register and transmit information about the current quality or status of the food with regard to its safety and digestibility. The nanosensors may be able to respond to environmental changes during storage (e.g. temperature, relative humidity and oxygen exposure), degradation products or microbial contamination (Bouwmeester et al. 2009). Nanosensors integrated into food packaging systems may detect spoilage-related changes, pathogens and chemical contaminants, hence eliminating the need for inaccurate expiration dates, and thereby providing real-time status of food freshness (Liao et al. 2005).

Time temperature integrators

Time–temperature indicators or integrators (TTIs) are designed to monitor record and translate whether a certain food product is safe to be consumed, in terms of its temperature history. This is particularly important when food is stored in conditions other than the optimal ones. For instance, if a product is supposed to be frozen, a TTI can indicate whether it had been inadequately exposed to higher temperatures and the time of exposure. The TTIs are categorized into three basic types, namely, abuse indicators, partial temperature history indicators, and full temperature history indicators. Abuse indicators, or critical temperature indicators, merely indicate whether a reference temperature has been achieved. Partial temperature history indicators integrate the time–temperature history only when the temperature exceeds a critical predetermined value. Finally, full temperature history indicators provide a continuous register of temperature changes with time (Singh 2000). The communication is usually manifested by a colour development (related to a temperature dependent migration of a dye through a porous material) or a colour change (using a temperature dependent chemical reaction or physical change). Timestrip® has developed a system (iStrip) for chilled foods, based on gold nanoparticles, which is red at temperatures above freezing. Accidental freezing leads to irreversible agglomeration of the gold nanoparticles resulting in loss of the red colour (Robinson and Morrison 2010).

Detection of gases

Food spoilage is caused by microorganisms whose metabolism produces gases which may be detected by several types of gas sensors which have been developed to translate chemical interactions between particles on a surface into response signals. Nanosensors to detect gases are usually based on metal oxides or, more recently, conducting polymer nanocomposites, which are able to quantify and/or identify microorganisms based on their gas emissions. Sensors based on conducting polymers (or electro active conjugated polymers) consist on conducting particles embedded into an insulating polymer matrix. The change in resistance of the sensors produces a pattern corresponding to the gas under investigation (Arshak et al. 2007). Conducting polymers are very important because of their electrical, electronic, magnetic and optical properties, which are related to their conjugated π electron backbones (Ahuja et al. 2007).

Polyene and polyaromatic conducting polymers such as polyaniline, polyacetylene and polypyrrole have been widely studied (Ahuja et al. 2007). Electrochemically polymerised 'conducting polymers' have a remarkable ability to switch between conducting oxidised (doped) and insulating reduced (undoped) states, which is the basis for several applications (Rajesh et al. 2004).

Nanosensors containing carbon black and polyaniline developed by Arshak et al. (2007) have been demonstrated to be able to detect and identify three food-borne pathogens by producing a specific response pattern for each microorganism.

O_2 sensors

There has been an increasing consensus in assuring complete absence of O_{2-} in oxygen-free food packaging systems and to this effect there is an interest to develop non-toxic and irreversible O_2 sensors with packaging done under vacuum or nitrogen. Lee et al. (2005) developed an UV-activated colorimetric O_2 indictor which uses TiO_2 NPs to photosensitize the reduction of methylene blue (MB) by triethanolamine in a polymer encapsulation medium using UV-A light. Upon UV irradiation, the sensor bleaches and remains colourless until it is exposed to oxygen, when its original blue colour is restored. The rate of colour change is proportional to the level of O_2 exposure (Gutiérrez-Tauste et al. 2007). Mills and Hazafy (2009) used nanocrystalline SnO_2 as a photosensitizer in a colorimetric O_2 indicator comprising a sacrificial electron donor (glycerol), a redox dye (MB) and an encapsulating polymer (hydroxyethyl cellulose). Exposure to UV-B light led to photobleaching of the indicator and photoreduction of MB by the SnO_2NPs. The colour of the films varied according to O_2 exposure—bleached when not exposed, and blue upon exposure.

Conclusion

Nanotechnology has not only improved the quality of foods by making them tastier, healthier and more nutritious but have also helped a lot in generating new food products, better packaging and storage techniques. Conversion of materials to its nano form helps in enhancement of their physiochemical properties and applications, e.g. titanium dioxide, used as an intense white pigment is opaque in nature. However, NPs of titanium dioxide are transparent and due to its physical nature, they are being used in transparent sunscreens, food packaging or plastic food containers.

Application of nanotechnology has enhanced the food texture and quality, reduced the fat content, compress nutrients, such as vitamins and minerals or can safeguard a product during storage, processing and transportation. In addition, nanomaterials are further researched to keep the product fresher with increased shelf life. Intelligent food packaging, incorporating nanosensors, could even provide consumers with information on the state of the food inside. Food packages are embedded with NPs that alert consumers when a product is no longer safe to eat. In fact, the technological advancement in the nano-industries will probably change the fabrication of the entire packaging industry. Nevertheless, many of their applications are currently at a beginning stage and most of them require a high quality of research and development for their safe application. The safety of NPs in food industry also offers challenge to government and industry both. The food processing industry must ensure the consumer confidence and acceptance of nano-foods safety. Although there are many citations regarding food grade NMs in the mean whilst there are reports which supports the toxicity of these NMs or it has not been analyzed yet. So, when it comes to the application of nanotechnology in industrial scale, it is important to evaluate the release of NPs into the environment and to estimate the subsequent levels of exposure to these materials. As the NPs can penetrate into the human organ and organelles, exposure time, exposure concentrations, sites of penetration, immune response and accumulation and retention of NPs in body and their subsequent effects should be assessed carefully.

Even though there are several researches going in the field of nanotechnology, still there has been insufficient scientific examination of naturally occurring nanosystems and the benefits they provide. The compulsory testing of nanomodified foods should be performed before they allowed to be introduced into the market. Standardised test procedures are required to study the impact of NPs on living cells for evaluation of the risk assessment on human exposure to NPs. Toxicology of NPs is poorly understood because of the lack of

Table 1 Different application of nanoscience and nanotechnology in agri-food sector

S. no.	Major field of research	Details of research	References
1	Nanostructures as pesticides	Ag NP, ZnO NP, Cu NP and TiO_2 NP are reported as a pesticide in agro-food chain	Lisha and Pradeep (2009), Kiaune and Singhasemanon (2011), Bouwmeester et al. (2009)
2	Nanostructures with synthesised nanostructure	Polymeric micelles: shell with amphiphilic block copolymers, core with hydrophobic region with nanoencapsulated lipids, flavouring agents, antibacterial agents, vitamins and antioxidant agents	Wu et al. (2012)
		Polymeric nanospheres are solid colloidal particles in which compounds are dissolved, entrapped, encapsulated, chemically bound, or adsorbed to the polymer matrix	Garcia-Castello et al. (2010)
		Nanocapsule: core oily liquid and surrounding single layer to entrap hydrophobic compounds, e.g. lipids, hydrophobic vitamins, antioxidants. Polymerosome has same function but its core is aqueous phase with surroundings of bilayer polymer	Letchford and Burt (2007), Flanagan and Singh (2006)
3	Lipid-based nanostructures	Nanoliposomes: a bilayered lipid vesicles that fuse with physiological bilayers (e.g. cell membranes), mediating the release of functional ingredients into the cells (e.g. encountering specific cellular enzymes, due to pH or thermo sensitivity or after the binding of antigen with the tagged antibody). In addition, they are biocompatible, less toxic, lack of immune system activation. Used for encapsulating and control ingredient delivery in functional food (e.g. flavours and nutrients), enhancing their bioavailability, stability and shelf life (e.g. milk proteins), and ability to incorporate antimicrobials that could aid in the protection of food products against microbial contamination	Mozafari et al. (2006), Taylor et al. (2005), Jesorka and Orwar (2008), Mozafari et al. (2008)
		Archaeosomes: prepared from archaeobacterial membrane lipids which is thermostable and stress resistant and are well-tolerated in vivo (murine models). They are an ideal carrier for protection of food supplements, such as antioxidants, during food processing (e.g. against chemical influences)	Patel et al. (2000), Omri et al. (2003)
		Nanocochleates: they comprise a multilayered structure consisting of a continuous, solid lipid layer sheet rolled up in a spiral fashion with little or no internal aqueous space, which can also encapsulate and deliver both hydrophilic and hydrophobic compounds. These lipid-based nanostructures deliver their inside content to target cells through fusion mechanisms. Their solid layer protects the 'encochleated' material from harsh environmental conditions (e.g. pH) or enzymes, being able to resist the degradation in the gastrointestinal tract, which makes them attractive carriers for oral delivery. They protect micronutrients and antioxidants from degradation during manufacture and storage	Mozafari et al. (2006), Zarif (2003), Chaudhry et al. (2008)

Table 1 continued

S. no.	Major field of research	Details of research	References
		Nanostructured lipid carrier (NLC): NLC is composed of a blend of solid lipid (melting point above 40 °C) within very tiny nanocompartments of liquid lipids (oil), which is solid at both body and room temperatures. NLC usually provides a high payload and prevents bioactive expulsion during storage. Hentschel et al. reported a successful encapsulation of β-carotene in NLC to be dispersed in beverages	Müller et al. (2007, 2011), Hentschel et al. (2008)
		Nanosized self-assembled structured liquid (NSSL)/nanodrops: These serve as liquid carriers, allowing penetration of health components, such as vitamins, minerals and phytochemicals. This technology has been used in the canola active oil by Shemen Industries and they report that the phytosterols added to the micelles can pass effectively the digestive system without breaking down. Additionally, inhibiting the move of cholesterol from the digestive system into the blood stream	Garti and Aserin (2005), Shin et al. (2005)
4	Nanotube membrane	Carbon nano tubes: tube-shaped structures; having interesting features for food packaging to improve its mechanical properties. It has nanotubes demonstrated powerful antimicrobial activity and that *Escherichia coli* died on immediate contact with long, thin nanotubes	Kang et al. (2007)
5	Functional food i.e. nutraceuticals, colourants, flavour enhancer etc.	Incorporation of functional ingredients with NEs, micelles, liposome, NPs, cubosomes etc. Different natural polymers such as albumin (protein), gelatin (protein), alginate (saccharide), collagen (protein), chitosan and pectin (saccharides), α-lactalbumin (milk protein) and zein (corn protein) which are nanostructured vitamins, antimicrobials, antioxidants, probiotics, prebiotics, peptides and proteins, carotenoids, omega fatty acids, flavourings, colourants and preservatives etc	Weiss et al. (2008), Chen et al. (2010), Sozer and Kokini (2009), Chen and Subirade (2005), Hu et al. (2008)
		To provide moisture and oxygen barrier inorganic NMs are used, e.g. $nSiO_2$ (E551), magnesium oxide (E530) and TiO_2 NP	Beyer et al. (1996)
		Ag NP is used for antibacterial 'active' coating because of its antibacterial activity	Chaudhry and Groves (2010)
		The administration of ω-3 polyunsaturated fatty acids is effective in preventing diseases. However, they require both stabilization procedures and protection against deterioration factors since they are highly sensitive to oxidation	Lavie et al. (2009), Ruxton et al. (2004)
		Two systems based on casein (casein nanostructures and reformed casein micelles) showed remarkable protective effect against docosahexaenoic acid oxidation. These systems proved to have a good colloidal stability and to preserve the effect of their functional ingredient up to 37 days at 4 °C	Zimet et al. (2011)

Table 1 continued

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)

Table 1 continued

S. no.	Major field of research	Details of research	References
		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)

Table 1 continued

S. no.	Major field of research	Details of research	References
		Zein nanostructures (corn protein) have been used as a vehicle of flavour compounds and essential oils (e.g. thymol and carvacrol), because they have the potential to form a tubular network resistant to microorganisms	Sozer and Kokini (2009); Wu et al. (2012)
		α-lactalbumin nanotube (obtained from milk protein) has been proposed to encapsulate nutraceuticals (e.g. vitamins) or to mask disagreeable flavour/odour compounds	Graveland-Bikker and De Kruif (2006), Srinivas et al. (2010)
		NanoCluster™, from RBC Life Sciences® Inc. (Irving, TX, USA), is another delivery system for food products, e.g. Slim Shake Chocolate, which incorporates silica NPs that are coated with cocoa to enhance the chocolate flavour	Carla et al. (2013), Bugusu et al. (2011), Cushen et al. (2012)
		The colour of the food products can be altered by nanoemulsion technology NEs of β-carotene, an oil-soluble pigment compound	Astete et al. (2009)
6	Nanofiltration	Nanofiltration in combination with powdered activated carbon to remove effluent organic matter from a municipal wastewater	Kazner et al. (2008)
		Nanofiltration membrane technologies have been applied to the dairy industry to treat water for further reuse in its processes and also to improve product quality	Cuartas-Uribe et al. (2007)
		Nanofiltration in combination with nanofiltration allowed to recover almost all available polyphenols, which are considered as pollutants, and to use these subproducts for preparing food, cosmetic and pharmaceutical formulations	Garcia-Castello et al. (2010)
		Xylooligosaccharides have food, medical, and pharmaceutical applications. It was possible to fractionate and purify xylooligosaccharides from monosaccharides and other low-molecular mass materials, such as salts, from rice husk xylan using nanofiltration; the concentrate presented a purity of over 91 % and an overall yield of 71 %	Vegas et al. (2008)
		Concentrated rosemary extract through nanofiltration has application as preservative and functional ingredient in the food, cosmetic, nutraceutical and medical areas	Peshev et al. (2011)
		The capability of the Duramem® 200 (Evonik MET Ltd., Wembley, UK) nanofiltration membrane to separate monophenolic acids from higher molecular mass antioxidant compounds in the extracts was observed with a molecular mass cut-off of 200 Da at a pressure of 20 bar	Sun et al. (2009)
		Researchers were able to concentrate roselle extract from 4 to 25 g of total soluble solids per 100 g, with 100 % retention of anthocyanins using ten nanofiltration flat-sheet membranes and eight tight ultrafiltration membranes	Cissé et al. (2011)

Table 1 continued

S. no.	Major field of research	Details of research	References
7	Food safety	Nanobiorecognition: it is the conjugation of biomolecules with nanomaterials for the detection of contamination and infectious diseases	Tallury et al. (2010)
		Nanobarcodes (synthetic DNA barcode) have been used in to detect the presence of food pathogens by measuring the reaction using a fluorescent probe under ultraviolet light. When the DNA barcodes, present in the films, conjugate with the tagged pathogens, the derived compound fluoresces, allows monitoring the presence of a defined pathogen	Brody et al. (2008)
		Immobilized oligonucleotide probes to magnetic NPs have been used to detect the contamination with *Listeria monocytogenes* cells of 10 CFU/mL in milk samples. However, this detection included a PCR reaction that confirmed a dose-dependent inhibitory effect	Amagliani et al. (2006)
		University of Pennsylvania, USA and Monell Chemical Senses Center, USA have used nanosized carbon tubes (as transmitter) coated with strands of DNA (as a sensor) to create nanosensors with the ability to detect odours and tastes	Brody et al. (2008)
		Electronic tongue nanosensors to detect substances in parts per trillion, which could be used to trigger colour changes in food packages to alert consumers when food is spoiled	Scampicchio et al. (2008)
		Functionalized single-walled CNT with multivalent carbohydrate ligands on their surface used for an efficient capture/detection of pathogenic *E. coli* cells	Gu et al. (2008)
		Nanofunctionalized gold electrode applied for rapid quantification of bacteria in milk, based on the catalysis of lipid peroxidation on cell membrane of bacteria by nanoporous gold film (detection range 1.1×10^3–2.5×10^7 CFU/mL within 1 h)	Wang et al. (2012)
8	Food packaging	Ag-NPs have capacity to restrain bacterial growth. 1–2% of Ag NP when included in low-density polyethylene (LDPE) packages in terms of microbial and sensory factors of dried barberry, microbial growth inhibition (bacteria and mould) and sensorial parameters (taste, aroma, appearance and total acceptance) were significantly increased	Jun et al. (2007), Motlagh et al. (2012)
		Nanostructured aluminium platelets have been self-assembled into wagon-wheel (nano-wheel) structures in order to improve barrier and mechanical properties of plastics	Mössinger et al. (2007)

Table 1 continued

S. no.	Major field of research	Details of research	References
		Montmorillonite clay has also been widely used as nano component of polymers such as polyethylene, nylon, polyvinyl chloride and starch and functioning as oxygen and carbon dioxide blockers, promoting an increase of the moisture of fresh meat and other food	Lan and Bayer (2011)
		Biodegradable nanocomposite food packages have been developed by pumping carbohydrates and clay fillers through high shear cells, films can be produced with exfoliated clay layers. These are very efficient as moisture barriers and increase the film strength significantly. Starch and chitosan are two of the most studied biodegradable matrices	Weiss et al. (2006)
		Montmorillonite and kaolinite clays showed good potential as compatible filler-polymer systems	Arora and Padua (2010)
		CNT can also be used in food packaging for improving mechanical properties and having powerful antimicrobial effect.	Brody et al. (2008), Lord (2008)
		Nanosensors integrated with food packages can be the emerging trends in the coming future. Photonic crystals used to produce unique food packaging material that changes colour; also they are successfully used in apple juice to detect sugar composition	Pursiainen et al. (2007), Brody et al. (2008), Malinin et al. (2012)
		Active cellulose-based packaging packaging guarantees the lysozyme lytic (and therefore, antimicrobial) activity against the *Micrococcus lysodeikticus* cell wall	Mascheroni et al. (2010)

validated test methods and the inconsistency in the reported data. The inconsistency in the published data is due to the improper characterisation of NPs and the interferences induced by the NPs in the assay system. Hence, the regulatory bodies and the policy makers should provide the guidance document for the validated protocols, safe uses and the disposal of the NPs. The application of the nanoscience and nanotechnology has also increased enormously other than food sector such as nanostructures as pesticides, polymeric nanostructures in drug delivery/increase the bioavailability, flavour enhancement etc. (Table 1). In the long term nanoscience and nanotechnology in food may be emerged as a new area of study and/or research which will be known as 'nano-food technology'.

Acknowledgments Chancellor and Vice Chancellor, VIT University, Vellore, TN, India is acknowledged for providing financial help for the project under the category of RGEMS-VC Fund, VIT.

References

Acosta E (2009) Bioavailability of nanoparticles in nutrient and nutraceutical delivery. Curr Opin Colloid Interface Sci 14(1):3–15

Adame D, Beall GW (2009) Direct measurement of the constrained polymer region inpolyamide/clay nanocomposites and the implications for gas diffusion. Appl Clay Sci 42:545–552

Ahuja T, Mir IA, Kumar D, Rajesh (2007) Biomolecular immobilization on conducting polymers for biosensing applications. Biomaterials 28:791–805

Alexandre M, Dubois P (2000) Polymer-layered silicate nanocomposites: preparation, properties and uses of a new class of materials. Mater Sci Eng R 28:1–63

Alexandre B, Langevin D, Médéric P, Aubry T, Couderc H, Nguyen QT, Saiter A, Marais S (2009) Water barrier properties of polyamide 12/montmorillonitenanocomposite membranes: structure and volume fraction effects. J Memb Sci 328(1–2):186–204

Amagliani G, Omiccioli E, del Campo A, Bruce IJ, Brandi G, Magnani M (2006) Development of a magnetic capture hybridization-PCR assay for *Listeria monocytogenes* direct detection in milk samples. J Appl Microbiol 100:375–383

Ankola DD, Viswanad B, Bhardwaj V, Ramarao P, Kumar MN (2007) Development of potent oral nanoparticulate formulation of coenzyme Q10 for treatment of hypertension: can the simple nutritional supplements be used as first line therapeutic agents for prophylaxis/therapy? Eur J Pharm Biopharm 67:361–369

Anpo M, Kishiguchi S, Ichihashi Y, Takeuchi M, Yamashita H, Ikeue K, Morin B, Davidson A, Che M (2001) The design and development of second-generation titanium oxide photocatalysts able to operate under visible light irradiation by applying a metal ion-implantation method. Res Chem Intermed 27(4–5):459–467

Anton N, Benoit JP, Saulnier P (2008) Design and production of nanoparticles formulated from nano-emulsion templates—a review. J Control Release 128:185–199

Arora A, Padua GW (2010) Review: nanocomposites in food packaging. J Food Sci 75:R43–R49

Arshak K, Adley C, Moore E, Cunniffe C, Campion M, Harris J (2007) Characterisation of polymer nanocomposite sensors for quantification of bacterial cultures. Sens Actuators B 126:226–231

Astete CE, Sabliov CM, Watanabe F, Biris A (2009) Ca^{2+} cross-linked alginic acid nanoparticles for solubilization of lipophilic natural colorants. J Agric Food Chem 57:7505–7512

Azizi SMAS, Alloin F, Dufresne A (2005) Review of recent research into cellulosic whiskers, their properties and their application in nanocomposite field. Biomacromolecules 6:612–626

Beyer PL, Jach TE, Zak DL, Jerome RA, Debrincat FP (1996) Edible products having inorganic coatings. US patent 5741505

Bouwmeester H, Dekkers S, Noordam MY, Hagens WI, Bulder AS, de Heer C, ten Voorde SE, Wijnhoven SW, Marvin HJ, Sips AJ (2009) Review of health safety aspects of nanotechnologies in food production. Regul Toxicol Pharmacol 53:52–62

Brody AL, Bugusu B, Han JH, Sand CK, McHugh TH (2008) Innovative food packaging solutions. J Food Sci 73:R107–R116

Bugusu B, Lay-Ma UV, Floros JO (2011) Products and their commercialization. In: Frewer LJ, Norde W, Fisher A, Kampers F (eds) Nanotechnology in the agri-food sector—implications for the future. Wiley-VCH, Weinheim, pp 149–170

Carla ML, José RF, Paula ML (2013) Application of nanotechnology in the agro-food sector. Food Technol Biotechnol 51:183–197

Carretero MI, Pozo M (2009) Clay and non-clay minerals in the pharmaceutical industry: part I. Excipients and medical applications. Appl Clay Sci 46:73–80

Center for Biological Nanotechnology (2001) http://www.vitamincity.com/umichnanobio.htm. Accessed 01 Dec 2013

Chaudhry Q, Groves K (2010) Nanotechnology Applications for Food Ingredients, Additives and Supplements. In: Chaudhry Q, Castle L, Watkins R (eds) Nanotechnologies in Food. RSC Publishing, Cambridge, pp 69–85

Chaudhry Q, Scotter M, Blackburn J, Ross B, Boxall A, Castle L et al (2008) Applications and implications of nanotechnologies for the food sector. Food Addit Contam A 25:241–258

Chawengkijwanich C, Hayata Y (2008) Development of TiO_2 powder-coated food packaging film and its ability to inactivate *Escherichia coli* in vitro and in actual tests. Int J Food Microbiol 123(3):288–292

Chen B, Evans JRG (2005) Thermoplastic starch–clay nanocomposites and their characteristics. Carbohydr Polym 61:455–463

Chen L, Subirade M (2005) Chitosan/β-lactoglobulin core–shell nanoparticles as nutraceutical carriers. Biomaterials 26:6041–6053

Chen HD, Weiss JC, Shahidi F (2006) Nanotechnology in nutraceuticals and functional foods. Food Technol 60:30–36

Chen YC, Yu SH, Tsai GJ, Tang DW, Mi FL, Peng YP (2010) Novel technology for the preparation of self-assembled catechin/gelatin nanoparticles and their characterization. J Agric Food Chem 58:6728–6734

Cheng Q, Li C, Pavlinek V, Saha P, Wang H (2006) Surface-modified antibacterial TiO_2/Ag^+ nanoparticles: preparation and properties. Appl Surf Sci 252:4154–4160

Choi W, Termin A, Hoffmann MR (1994) The role of metal ion dopants in quantum size TiO_2: correlation between photoreactivity and charge carrier recombination dynamics. J Phys Chem 98:13669–13679

Cioffi N, Torsi L, Ditaranto N, Tantillo G, Ghibelli L, Sabbatini L, Bleve-zacheo T, D'alessio M, Zambonin PG, Traversa E (2005) Copper nanoparticle/polymer composites with antifungal and bacteriostatic properties. Chem Mater 17:5255–5262

Cissé M, Vaillant F, Pallet D, Dornier M (2011) Selecting ultrafiltration and nanofiltration membranes to concentrate anthocyanins from roselle extract (*Hibiscus sabdariffa* L.). Food Res Int 44:2607–2614

Cuartas-Uribe B, Alcaina-Miranda MI, Soriano-Costa E, Bes-Pia A (2007) Comparison of the behavior of two nanofiltration membranes for sweet whey demineralization. J Dairy Sci 90:1094–1101

Cushen M, Kerry J, Morris M, Cruz-Romero M, Cummins E (2012) Nanotechnologies in the food industry—recent developments, risks and regulation. Trends Food Sci Technol 24:30–46

Cushing BL, Vladimir LK, Charles JO (2004) Recent advances in the liquid-phase syntheses of inorganic nanoparticles. Chem Rev 104:3893–3946

Cyras VP, Manfredi LB, Ton-that MT, Vázquez A (2008) Physical and mechanical properties of thermoplastic starch/montmorillonite nanocomposite films. Carbohydr Polym 73:55–63

Dalmas F, Cavaillé JY, Gauthier C, Chazeau L, Dendievel R (2007) Viscoelastic behavior and electrical properties of flexible nanofiber filled polymer nanocomposites. Influence of processing conditions. Compos Sci Technol 67:829–839

Danie KJ, Shivendu R, Nandita D, Proud S (2013) Nanotechnology for tissue engineering: need, techniques and applications. J Pharm Res 7(2):200–204

Ezhilarasi PN, Karthik P, Chhanwal N, Anandharamakrishnan C (2012) Nanoencapsulation techniques for food bioactive components: a review. Food Bioprocess Technol 6(3):628–647

Fernández A, Cava D, Ocio MJ, Lagaron JM (2008) Perspectives for biocatalysts in food packaging. Trends Food Sci Technol 19(4):198–206

Flanagan J, Singh H (2006) Microemulsions: a potential delivery system for bioactives in food. Crit Rev Food Sci Nutr 46:221–237

Food Safety Authority of Ireland (2008) The relevance for food safety of applications of nanotechnology in the food and feed industries. http://www.fsai.ie/WorkArea/DownloadAsset.aspx?id=7858. Accessed 1 Dec 2013

Fujishima A, Rao TN, Tryk DA (2000) Titanium dioxide photocatalysis. J Photochem Photobiol C 1(1):1–21

Garcia-Castello E, Cassano A, Criscuoli A, Conidi C, Drioli E (2010) Recovery and concentration of polyphenols from olive mil wastewaters by integrated membrane system. Water Res 44:3883–3892

Garrido-Ramirez EG, Theng BKG, Mora ML (2010) Clays and oxide minerals as catalysts and nanocatalysts in Fenton-like reactions—a review. Appl Clay Sci 47:182–192

Garti N, Aserin A (2005) Microemulsions for solubilization and delivery of nutraceuticals and drugs. In: Benita S (ed) Microencapsulation: methods and industrial applications, drugs and the pharmaceutical sciences, vol 158. CRC Press, Taylor and Francis, Boca Raton, pp 345–428

Gelover S, Gómez LA, Reyes K, Leal MT (2006) A practical demonstration of water disinfection using TiO_2 films and sunlight. Water Res 40:3274–3280

Goettler L, Lee K, Thakkar H (2007) Layered silicate reinforced polymer nanocomposites: development and applications. Polym Rev 47:291–317

Gopinath S, Sugunan S (2007) Enzymes immobilized on montmorillonite K 10: effect of adsorption and grafting on the surface properties and the enzyme activity. Appl Clay Sci 35(1–2):67–75

Graveland-Bikker JF, De Kruif CG (2006) Unique milk protein based nanotubes: food and nanotechnology meet. Trends Food Sci Technol 17:196–203

Green RJ, Murphy AS, Schulz B, Watkins BA, Ferruzzi MG (2007) Common tea formulations modulate in vitro digestive recovery of green tea catechins. Mol Nutr Food Res 51:1152–1162

Gruère G, Narrod C, Abbott L (2011) Agriculture, food, and water nanotechnologies for the poor opportunities and constraints policy Brief 19, June 2011. International Food Policy Research Institute (IFPRI), Washington, DC. http://www.ifpri.org/sites/default/files/publications/ifpridp01064.pdf Accessed 05 Dec 2013

Gu HW, Ho PL, Tong E, Wang L, Xu B (2003) Presenting vancomycin on nanoparticles to enhance antimicrobial activities. Nano Lett 3:1261–1263

Gu L, Luo PG, Wang H, Meziani MJ, Lin Y, Veca LM, Cao L, Lu F, Wang X, Quinn RA, Wang W, Zhang P, Lacher S, Sun YP (2008) Single-walled carbon nanotube as a unique scaffold for the multivalent display of sugars. Biomacromolecules 9:2408–2418

Gutiérrez-Tauste D, Domènech X, Casañ-Pastor N, Ayllón JA (2007) Characterization of methylene blue/TiO_2 hybrid thin films prepared by the liquid phase deposition (LPD) method: application for fabrication of light-activated colorimetric oxygen indicators. J Photochem Photobiol A 187:45–52

Halliday J (2007) EFSA opens the floor on nanotechnology. http://www.foodnavigator.com/Financial-Industry/EFSA-opens-the-floor-on-nanotechnology. Accessed 28 Nov 2013

Hebbar UH, Raghavarao KSMS (2007) Extraction of bovine serum albumin using nanoparticulate reverse micelles. Process Biochem 42:1602–1608

Helbert W, Cavaillé CY, Dufresne A (1996) Thermoplastic nanocomposites filled with wheat straw cellulose whiskers. Part I: processing and mechanical behaviour. Polym Compos 17(4):604–611

Hench LL, West JK (1990) The sol–gel process. Chem Rev 90:33–72

Hentschel A, Gramdorf S, Muller RH, Kurz T (2008) β-Carotene loaded nanostructured lipid carriers. J Food Sci 73:N1–N6

Hu B, Pan C, Sun Y, Hou Z, Ye H, Zeng X (2008) Optimization of fabrication parameters to produce chitosan–tripolyphosphate nanoparticles for delivery of tea catechins. J Agric Food Chem 56:7451–7458

Huang L, Li DQ, Lin YJ, Wei M, Evans DG, Duan X (2005) Controllable preparation of nano-MgO and investigation of its bactericidal properties. J Inorg Biochem 99:986–993

Huang Q, Yu H, Ru Q (2010) Bioavailability and delivery of nutraceuticals using nanotechnology. J Food Sci 75(1):R50–R57

Jesorka A, Orwar O (2008) Liposomes: technologies and analytical applications. Annu Rev Anal Chem 1:801–832

Jia X, Li Y, Cheng Q, Zhang S, Zhang B (2007) Preparation and properties of poly(vinyl alcohol)/silica nanocomposites derived from copolymerization of vinyl silica nanoparticles and vinyl acetate. Eur Polym J 43:1123–1131

Johnston CT (2010) Probing the nanoscale architecture of clay minerals. Clay Miner 45(3):245–279

Jordan J, Jacob KI, Tannenbaum R, Sharaf MA, Jasiuk I (2005) Experimental trends in polymer nanocomposites—a review. Mater Sci Eng A 393(1–2):1–11

Joseph T, Morrison M (2006) Nanotechnology in agriculture and food: a nanoforum report. Institute of Nanotechnology. http://www.nanoforum.org. Accessed 5 Feb 2013

Jun SK, Eunye K, Kyeong NY, Jong-Ho K, Sung JP, Hu JL, So HK, Young KP, Yong HP, Cheol-Yong H, Yong-Kwon K, Yoon-Sik L, Dae HJ, Myung-Haing C (2007) Antimicrobial effects of silver nanoparticles. Nanomed Nanotechnol 3:95–101

Kang S, Pinault M, Pfefferle LD, Elimelech M (2007) Single-walled carbon nanotubes exhibit strong antimicrobial activity. Langmuir 23:8670–8673

Kazner C, Wintgens T, Melin T, Baghoth S, Sharma S, Amy G (2008) Comparing the effluent organic matter removal of direct NF and powdered activated carbon/NF as high quality pretreatment options for artificial groundwater recharge. Water Sci Technol 57:821–827

Kiaune L, Singhasemanon N (2011) Pesticidal copper (I) oxide: environmental fate and aquatic toxicity. In: Whitacre DM (ed) Reviews of environmental contamination and toxicology, vol 213. Springer, Cham

Kim JY, Il Han S, Hong S (2008) Effect of modified carbon nanotube on the properties of aromatic polyester nanocomposites. Polymer 49:3335–3345

Kinemuchi Y, Keiichi M, Channalong S, Chu-Hyun C, Hisayuki S, Weihua J, Kiyoshi Y (2003) Nanosize powders of aluminum nitride synthesized by pulsed wire discharge. J Am Ceram Soc 86:420–424

Kriegel C, Arrechi A, Kit K, McClements DJ, Weiss J (2008) Fabrication, functionalization, and application of electrospun bipolymer nanofibers. Crit Rev Food Sci 48:775–797

Kumar R, Münstedt H (2005) Silver ion release from antimicrobial polyamide/silver composites. Biomaterials 26: 2081–2088

Kvítek L, Panáček A, Soukupová J, Kolář M, Večeřová R, Prucek R, Holecová M, Zbořil R (2008) Effect of surfactants and polymers on stability and antibacterial activity of silver nanoparticles (NPs). J Phys Chem C 112(15):5825–5834

Lagaron JM, Catalá R, Gavara R (2004) Structural characteristics defining high barrier polymeric materials. Mater Sci Technol 20:1–7

Lan T, Bayer G (2011) Introduction to flame retardancy of polymer–clay nanocomposites. In: Mittal V (ed) Thermally stable and flame retardant polymer nanocomposites. Cambridge University Press, Cambridge, pp 161–185

Lavie CJ, Milani RV, Mehra MR, Ventura HO (2009) Omega-3 polyunsaturated fatty acids and cardiovascular diseases. J Am Coll Cardiol 54:585–594

Lee SK, Sheridan M, Mills A (2005) Novel UV-activated colorimetric oxygen indicator. Chem Mater 17(10):2744–2751

Letchford K, Burt H (2007) A review of the formation and classification of amphiphilic block copolymer nanoparticulate structures: micelles, nanospheres, nanocapsules and polymersomes. Eur J Pharm Biopharm 65:259–269

Li H, Zhao X, Ma Y, Zhai G, Li L, Lou H (2008a) Enhancement of gastrointestinal absorption of quercetin by solid lipid nanoparticles. J Control Release 346:160–168

Li Q, Mahendra S, Lyon DY, Brunet L, Liga MV, Li D, Alvarez PJJ (2008b) Antimicrobial nanomaterials for water disinfection and microbial control: potential applications and implications. Water Res 42(18):4591–4602

Li H, Li F, Wang L, Sheng J, Xin Z, Zhao L, Xiao H, Zheng Y, Hu Q (2009) Effect of nano-packing on preservation quality of Chinese jujube (*Ziziphus jujuba Mill*. var. *inermis* (Bunge) Rehd). Food Chem 114(2):547–552

Liao F, Chen C, Subramanian V (2005) Organic TFTs as gas sensors for electronic nose applications. Sens Actuators B 107(2):849–855

Liau SY, Read DC, Pugh WJ, Furr JR, Russell AD (1997) Interaction of silver nitrate with readily identifiable groups: relationship to the antibacterial action of silver ions. Lett Appl Microbiol 25:279–283

Limpens J, Schröder FH, de Ridder CM, Bolder CA, Wildhagen MF, Obermüller-Jevic UC et al (2006) Combined lycopene and vitamin E treatment suppresses the growth of PC-346C human prostate cancer cells in nude mice. J Nutr 136:1287–1293

Lisha KP, Pradeep T (2009) Enhanced visual detection of pesticides using gold nanoparticles. J Environ Sci Health B 44:697–705

Lopez-Rubio A, Gavara R, Lagaron JM (2006) Bioactive packaging: turning foods into healthier foods through biomaterials. Trends Food Sci Technol 17:567–575

Lord JB (2008) The food industry in the United States. In: Brody AL, Lord JB (eds) Developing new food products for a changing marketplace. CRS, Boca Raton, pp 1–23

Ludueña LN, Alvarez VA, Vasquez A (2007) Processing and microstructure of PCL/clay nanocomposites. Mater Sci Eng A 460–461:121–129

Luo PG, Stutzenberger FJ (2008) Nanotechnology in the detection and control of microorganisms. Adv Appl Microbiol 63:145–181

Maciejewski M, Brunner TJ, Loher SF, Stark WJ, Baiker A (2008) Phase transitions in amorphous calcium phosphates with different Ca/P ratios. Thermochim Acta 468:75–80

Maherani B, Arab-Tehrany E, Kheirolomoom A, Cleymand F, Linder M (2012) Influence of lipid composition on physicochemical properties of nanoliposomes encapsulating natural dipeptide antioxidant L-carnosine. Food Chem 134:632–640

Malinin AV, Zanishevskaja AA, Tuchin VV, Skibina YS, Silokhin IY (2012) Photonic crystal fibers for food quality analysis. In: Popp J, Drexler W, Tuchin VV, Matthews DL (eds) Biophotonics: photonic solutions for better health care, III, Proceedings of SPIE, vol 8427. SPIE, Bellingham

Maness PC, Smolinski S, Blake DM, Huang Z, Wolfrum EJ, Jacoby WA (1999) Bactericidal activity of photocatalytic TiO_2 reaction: toward an understanding of its killing mechanism. Appl Environ Microbiol 65(9):4094–4098

Mascheroni E, Capretti G, Marengo M, Iametti S, Mora L, Piergiovanni L, Bonomi F (2010) Modification of cellulose-based packaging materials for enzyme immobilization. Packag Technol Sci 23:47–57

Mattoso LHC, Medeiros ES, Baker AD, Avloni J, Wood DF, Orts WJ (2009) Electrically conductive nanocomposites made from cellulose nanofibrils and polyaniline. J Nanosci Nanotechnol 9:2917–2922

McClements DJ, Decker EA, Park Y, Weiss J (2009) Structural design principles for delivery of bioactive components in nutraceuticals and functional foods. Crit Rev Food Sci Nutr 49(6):577–606

Mills A, Hazafy D (2009) Nanocrystalline SnO2-based, UVB-activated, colourimetric oxygen indicator. Sens Actuators B 136(2):344–349

Mills A, Doyle G, Peiro AM, Durrant J (2006) Demonstration of a novel, flexible, photocatalytic oxygen-scavenging polymer film. J Photochem Photobiol A 177:328–331

Monteiro-Riviere NA, Nemanich RJ, Inman AO, Wang YY, Riviere JE (2005) Multi-walled carbon nanotube interactions with human epidermal keratinocytes. Toxicol Lett 155(13):377–384

Mora-Huertas CE, Fessi H, Elaissari A (2010) Polymer-based nanocapsules for drug delivery. Int J Pharm 385:113–142

Morones JR, Elechiguerra JL, Camacho A, Holt K, Kouri JB, Ramirez JT, Yacaman MJ (2005) The bactericidal effect of silver nanoparticles. Nanotechnology 16:2346–2353

Morris VJ (2006) Nanotechnology and its future in new product development. J Inst Food Sci Technol 20(3):15–17

Mössinger D, Hornung J, Lei S, De Feyter S, Höger S (2007) Molecularly defined shape-persistent 2D oligomers: the covalent-template approach to molecular spoked wheels. Angew Chem Int Ed 46:6802–6806

Motlagh NV, Mosavian MTH, Mortazavi SA, Tamizi A (2012) Beneficial effects of polyethylene packages containing micrometer-sized silver particles on the quality and shelf life of dried barberry (*Berberis vulgaris*). J Food Sci 77:E2–E9

Mozafari MR, Flanagan J, Matia-Merino L, Awati A, Omri A, Suntres ZE, Singh H (2006) Recent trends in the lipid-based nanoencapsulation of antioxidants and their role in foods. J Sci Food Agric 86:2038–2045

Mozafari MR, Johnson C, Hatziantoniou S, Demetzos C (2008) Nanoliposomes and their applications in food nanotechnology. J Liposome Res 18:309–327

Müller RH, Petersen RD, Hommoss A, Pardeike J (2007) Nanostructured lipid carriers (NLC) in cosmetic dermal products. Adv Drug Deliv Rev 59:522–530

Müller RH, Shegokar R, Keck CM (2011) 20 years of lipid nanoparticles (SLN and NLC): present state of development and industrial applications. Curr Drug Discov Technol 8:207–227

Nielsen LE (1967) Models for the permeability of filled polymer systems. J Macromol Sci 1(5):929–942

Omri A, Agnew BJ, Patel GB (2003) Short-term repeated-dose toxicity profile of archaeosomes administered to mice via intravenous and oral routes. Int J Toxicol 22:9–23

Patel GB, Agnew BJ, Deschatelets L, Fleming LP, Sprott GD (2000) In vitro assessment of archaeosome stability for developing oral delivery systems. Int J Pharm 194:39–49

Peshev D, Peeva LG, Peev G, Baptista IIR, Boam AT (2011) Application of organic solvent nanofiltration for concentration of antioxidant extracts of rosemary (*Rosmarinus officiallis* L.). Chem Eng Res Des 89:318–327

Petersson L, Oksman K (2006) Biopolymer based nanocomposites: comparing layeredsilicates and microcrystalline cellulose as nanoreinforcement. Compos Sci Technol 66:2187–2196

Podsiadlo P, Choi SY, Shim B, Lee J, Cuddihy M, Kotov NA (2005) Molecularly engineered nanocomposites: layer-by-layer assembly of cellulose nanocrystals. Biomacromolecules 6:2914–2918

Prashantha K, Soulestin J, Lacrampe MF, Krawczak P, Dupin G, Claes M (2009) Masterbatch-based multi-walled carbon nanotube filled polypropylene nanocomposites: assessment of rheological and mechanical properties. Compos Sci Technol 69(11–12):1756–1763

Pursiainen OLJ, Baumberg JJ, Winkler H, Viel B, Spahn P, Ruhl T (2007) Nanoparticle-tuned structural color from polymer opals. Opt Express 15:9553–9561

Qhobosheane M, Santra S, Zhang P, Tan WH (2001) Biochemically functionalized silica nanoparticles. Analyst 126(8):1274–1278

Qi LF, Xu ZR, Jiang X, Hu C, Zou X (2004) Preparation and antibacterial activity of chitosan nanoparticles. Carbohydr Res 339:2693–2700

Qiao R, Brinson LC (2009) Simulation of interphase percolation and gradients in polymer nanocomposites. Compos Sci Technol 69(3–4):491–499

Quintanar D, Allémann E, Fessi H, Doelker E (1998) Preparation techniques and mechanisms of formation of biodegradable nanoparticles from preformed polymers. Drug Dev Ind Pharm 24:1113–1128

Quintanilla-Carvajal MX, Camacho-Díaz BH, Meraz-Torres LS, Chanona-Pérez JJ, Alamilla-Beltrán L, Jimenéz-Aparicio A, Gutiérrez-López GF (2010) Nanoencapsulation: a new trend in food engineering processing. Food Eng Rev 2(1):39–50

Rabea EI, Badawy ME, Stevens CV, Smagghe G, Steurbaut W (2003) Chitosan as antimicrobial agent: applications and mode of action. Biomacromolecules 4(6):1457–1465

Radtchenko IL, Sukhorukov GB, Möhwald H (2002) Anovel method for encapsulationof poorly water-soluble drugs: precipitation in polyelectrolyte multilayer shells. Int J Pharm 242:219–223

Rajesh, Takashima W, Kaneto K (2004) Amperometric phenol biosensor based on covalent immobilization of tyrosinase onto an electrochemically prepared novel copolymer poly(*N*-3-aminopropylpyrrole-copolymer) film. Sens Actuators B 102:271–277

Reddy MP, Venugopal A, Subrahmanyam M (2007) Hydroxyapatite-supported Ag TiO_2 as *Escherichia coli* disinfection photocatalyst. Water Res 41:379–386

Rhim JW, Ng PKW (2007) Natural biopolymer-based nanocomposite films for packaging applications. Crit Rev Food Sci Nutr 47(4):411–433

Robertson JMC, Robertson PKJ, Lawton LA (2005) A comparison of the effectiveness of TiO_2 photocatalysis and UVA photolysis for the destruction of three pathogenic micro-organisms. J Photochem Photobiol A 175(1):51–56

Robinson DKR, Morrison MJ (2010) Nanotechnologies for food packaging: reporting the science and technology research trends: report for the ObservatoryNANO. http://www.observatorynano.eu/project/filesystem/files/Food%20Packaging%20Report%202010%20DKR%20Robinson.pdf. Accessed 15 Sep 2013

Ruxton CHS, Reed SC, Simpson MJA, Millington KJ (2004) The health benefits of omega-3 polyunsaturated fatty acids: a review of the evidence. J Hum Nutr Diet 17:449–459

Sadtler V, Rondon-Gonzalez M, Acrement A, Choplin L, Marie E (2010) PEO-covered nanoparticles by emulsion inversion point (eip) method. Macromol Rapid Commun 31(11):998–1002

Sadurní N, Solans C, Azemar N, García-Celma MJ (2005) Studies on the formation of O/W nano-emulsions, by low-energy emulsification methods, suitable for pharmaceutical applications. Eur J Pharm Sci 26(5):438–445

Sanchez-Garcia MD, Gimenez E, Lagaron JM (2008) Morphology and barrier properties of solvent cast composites of thermoplastic biopolymers and purified cellulose fibers. Carbohydr Polym 71:235–244

Sanguansri P, Augustin MA (2006) Nanoscale materials development—a food industry perspective. Trends Food Sci Technol 17(10):547–556

Scampicchio M, Ballabio D, Arecchi A, Cosio SM, Mannino S (2008) Amperometric electronic tongue for food analysis. Microchim Acta 163:11–21

Sharma AL, Singhal R, Kumar A, Rajesh, Pande KK, Malhotra BD (2004) Immobilization of glucose oxidase onto electrochemically prepared poly(aniline-co-fluoroaniline) films. J Appl Polym Sci 91(6):3999–4006

Shin MJ, Lee JH, Jang Y, Lee-Kim YC, Park E, Kim KM et al (2005) Micellar phytosterols effectively reduce cholesterol absorption at low doses. Ann Nutr Metab 49:346–351

Silva HD, Cerqueira MÂ, Vicente AA (2012) Nanoemulsions for food applications: development and characterization. Food Bioprocess Technol 5:854–867

Singh RP (2000) Scientific principles of shelf-life evaluation. In: Man D, Jones A (eds) Shelf-life evaluation of foods. Aspen, New York, pp 2–22. ISBN 978-0834217829

Soares NFF, Hotchkiss JH (1998) Naringinase immobilization in packaging films for reducing naringin concentration in grapefruit juice. J Food Sci 63:61–65

Sondi I, Salopek-Sondi B (2004) Silver nanoparticles as antimicrobial agent: a case study on *E. coli* as a model for Gram-negative bacteria. J Colloid Interface Sci 275:177–182

Sozer N, Kokini JL (2009) Nanotechnology and its applications in the food sector. Trends Biotechnol 27:82–89

Srinivas PR, Martin P, Tania QV, Qingrong H, Josef LK, Etta S, Hongda C, Charles MP, Karl EF, McDade-Ngutter C, Van H, Pamela S-R, Nancy M, Joseph MB, Johanna D, John M, Sharon AR (2010) Nanotechnology research: applications in nutritional sciences. J Nutr 140:119–124

Stark WJ, Pratsinis SE (2002) Aerosol flame reactors for manufacture of nanoparticles. Powder Technol 126:103–108

Sun J, Yao JY, Huang SX, Long X, Wang JB, García E (2009) Antioxidant activity of polyphenol and anthocyanin extracts from fruits of *Kadsura coccinea* (Lem.) AC Smith. Food Chem 117:276–281

Tadros T, Izquierdo P, Esquena J, Solans C (2004) Formation and stability of nano-emulsions. Adv Colloid Interface Sci 108–109:303–318

Tallury P, Malhotra A, Byrne ML, Santra S (2010) Nanobioimaging and sensing of infectious diseases. Adv Drug Deliv Rev 62:424–437

Tan W, Zhang Y, Szeto YS, Liao L (2008) A novel method to prepare chitosan/montmorillonite nanocomposites in the presence of hydroxyl-aluminum olygomeric cations. Compos Sci Technol 68(14):2917–2921

Tang C, Liu H (2008) Cellulose nanofiber reinforced poly (vinyl alcohol) composite film with high visible light transmittance. Compos A Appl Sci Manuf 39(10):1638–1643

Tang DW, Yu SH, Ho YC, Huang BQ, Tsai GJ, Hsieh HY et al (2013) Characterization of tea catechins-loaded nanoparticles prepared from chitosan and an edible polypeptide. Food Hydrocoll 30:33–41

Tankhiwale R, Bajpai SK (2009) Graft co-polymerization onto cellulose-based filter paper and its further development as silver nanoparticles-loaded antibacterial food packaging material. Colloids Surf, B 69(2):164–168

Taylor TM, Davidson PM, Bruce BD, Weiss J (2005) Liposomal nanocapsules in food science and agriculture. Crit Rev Food Sci Nutr 45:587–605

Ullmann M, Friedlander SK, Schmidt-Ott A (2002) Nanoparticle formation by laser ablation. J Nanopart Res 4:499–509

Uyama H, Kuwabara M, Tsujimoto T, Nakano M, Usuki A, Kobayashi S (2003) Green nanocomposite from renewable resources: plant oil-clay hybrid materials. Chem Mater 15:2492–2494

Vegas R, Moure A, Domínguez H, Parajó JC, Alvarez JR, Luque S (2008) Evaluation of ultra- and nanofiltration for refining soluble products from rice husk xylan. Bioresour Technol 99:5341–5351

Vladimiriov V, Betchev C, Vassiliou A, Papageorgiou G, Bikiaris D (2006) Dynamic mechanical and morphological studies of isotactic polypropylene/fumed silica nanocomposites with enhanced gas barrier properties. Compos Sci Technol 66:2935–2944

Walde P, Ichikawa S (2001) Enzymes inside lipid vesicles: preparation, reactivity and applications. Biomol Eng 18:143–177

Wang XY, Gu F, Yin F, Tu YF (2012) Rapid detection of microorganisms in milk using an in-situ prepared nano-functionalized gold electrode. Chin J Anal Chem 40:657–662

Warheit DB, Laurence BR, Reed KL, Roach DH, Reynolds GAM, Webb TR (2004) Comparative pulmonary toxicity assessment of single-wall carbon nanotubes in rats. Toxicol Sci 77:117–125

Weiss J, Takhistov P, McClements DJ (2006) Functional materials in food nanotechnology. J Food Sci 71(9):107–116

Weiss J, Decker EA, McClements DJ, Kristbergsson K, Helgason T, Awad T (2008) Solid lipid nanoparticles as delivery systems for bioactive food components. Food Biophys 3(2):146–154

Wu Y, Luo Y, Wang Q (2012) Antioxidant and antimicrobial properties of essential oils encapsulated in zein nanoparticles prepared by liquid–liquid dispersion method. LWT Food Sci Technol 48:283–290

Xiao-e L, Green ANM, Haque SA, Mills A, Durrant JR (2004) Light-driven oxygen scavenging by titania/polymer nanocomposite films. J Photochem Photobiol A 162:253–259

Xiong HG, Tang SW, Tang HL, Zou P (2008) The structure and properties of a starch-based biodegradable film. Carbohydr Polym 71:263–268

Yin LJ, Chu BS, Kobayashi I, Nakajima M (2009) Performance of selected emulsifiers and their combinations in the preparation of [beta]-carotene nanodispersions. Food Hydrocoll 23(6):1617–1622

Yu H, Xu X, Chen X, Lu T, Zhang P, Jing X (2007) Preparation and antibacterial effects of PVA-PVP hydrogels containing silver nanoparticles. J Appl Polym Sci 103:125–133

Zarif L (2003) Nanocochleate cylinders for oral & parenteral delivery of drugs. J Liposome Res 13:109–110

Zeng H, Gao C, Wang Y, Watts PCP, Kong H, Cui X, Yan D (2006) In situ polymerization approach to multiwalled carbon nanotubes-reinforced nylon 1010 composites: mechanical properties and crystallization behavior. Polymer 47:113–122

Zhang L, Zheng Y, Chow MSS, Zuo Z (2004) Investigation of intestinal absorption and disposition of green tea catechins by CaCO-2 monolayer model. Int J Pharm 287:1–12

Zhou X, Shin E, Wang KW, Bakis CE (2004) Interfacial damping characteristics of carbon nanotube-based composites. Compos Sci Technol 64(15):2425–2437

Zimet P, Rosenberg D, Livney YD (2011) Re-assembled casein micelles and casein nanoparticles as nano-vehicles for omega-3 polyunsaturated fatty acids. Food Hydrocoll 25(5): 1270–1276