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# Nanoscience and nanotechnologies in food industries: opportunities and research trends

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Pour faciliter la lecture, les parties essentielles en ce qui concerne la coenzyme Q10 NOVA ©SOL (hydrophile et micellaire) et la société Aquanova sont colorées en vert: pages 3-5-14-15-18

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**Abstract** Nanomaterials have gained importance in various fields of science, technology, medicine, colloid technologies, diagnostics, drug delivery, personal care applications and others due to their small size and unique physico-chemical characteristic. Apart from above mentioned area, it is also extensively being used in food sector specifically in preservation and packaging. The future applications in food can also be extended to improve the shelf life, food quality, safety, fortification and biosensors for contaminated or spoiled food or food packaging. Different types and shapes of nanomaterials are being employed depending upon the need and nature of the food. Characterisation of these nanomaterials is essential to understand the interaction with the food matrix and also with biological compartment. This review is focused on application of nanotechnology in food industries. It also gives insight on commercial

products in market with usage of nanomaterials, current research and future aspects in these areas. Currently, they are being incorporated into commercial products at a faster rate than the development of knowledge and regulations to mitigate potential health and environmental impacts associated with their manufacturing, application and disposal. As nanomaterials are finding new application every day, care should be taken about their potential toxic effects.

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

## Introduction

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

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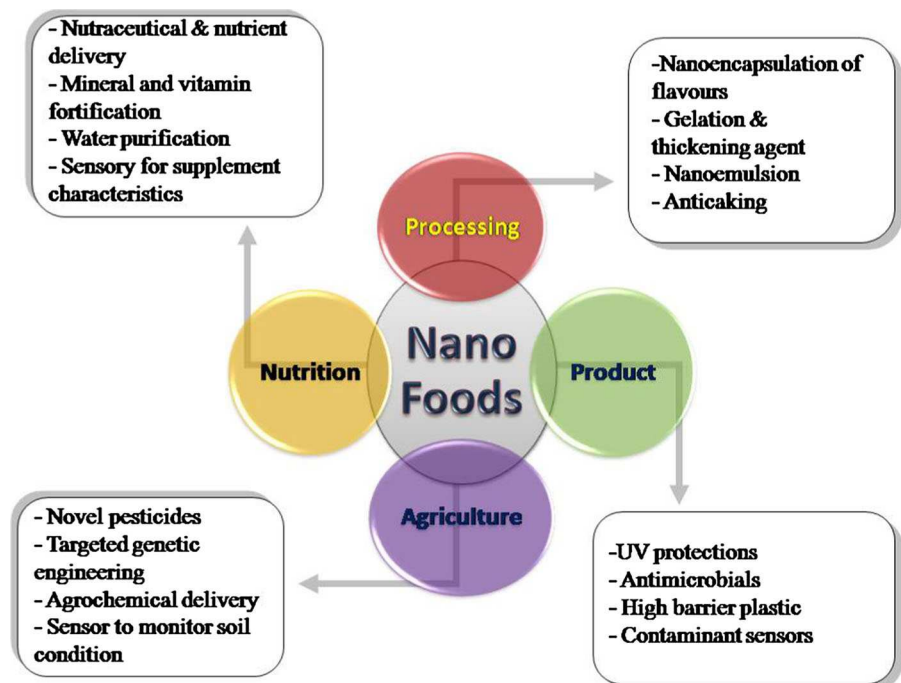
forms are being used in food packaging and food ingredients i.e. food additives, nutraceuticals etc. (Chen et al. 2006), but over the long term focus can be brought upon controlled release of nano-encapsulated food ingredients or nutrients (Morris 2006). Nanotechnology can also improve the water dispersability, 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  $M_x(\text{Al}_{4-x}\text{Mg}_x)\text{Si}_8\text{O}_{20}(\text{OH})_4$ . 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  $\text{Na}^+$  and  $\text{Ca}^{2+}$ ). 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 (Pettersson 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  $\text{CO}_2$  from the drink and the ingress of  $\text{O}_2$  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  $\text{O}_2$  scavengers and passive nanocomposite clay particles to enhance the barrier properties for retaining  $\text{CO}_2$  and keeping  $\text{O}_2$  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 (Sadtlter 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,  $\beta$ -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- $\alpha$ -tocopherol acetate, vitamins A, D, D3, E, and K and omega three fatty acids) and natural colourants ( $\beta$ -carotene, apocotenol, 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).

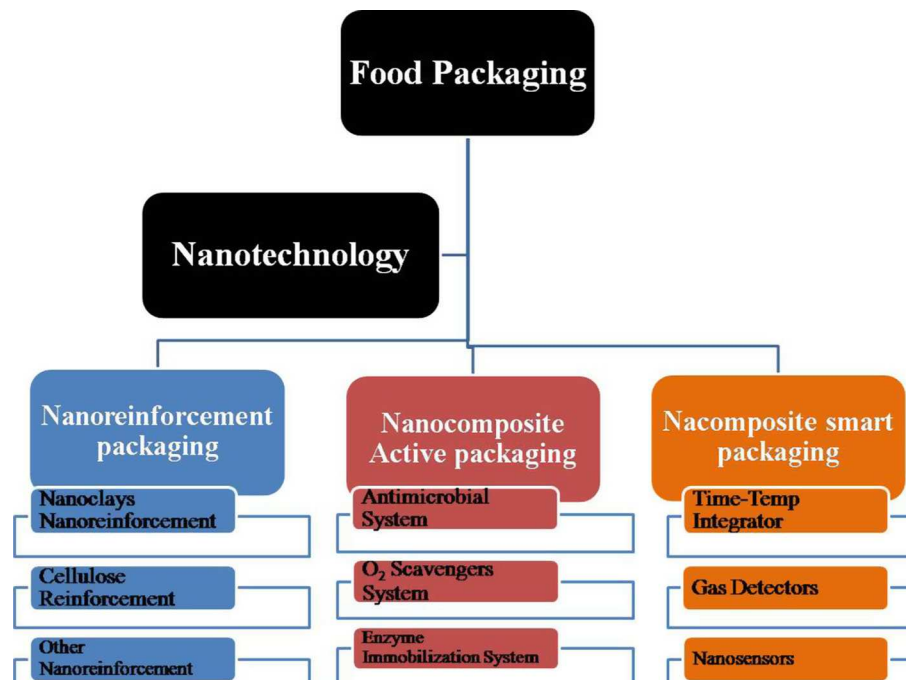
Unilever has made ice cream healthier without compromising on taste through the application of NEs. The objective is to produce ice cream with lower fat content, achieving a fat reduction from the actual 16–1 % (Silva et al. 2012).

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 (Dalmás 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

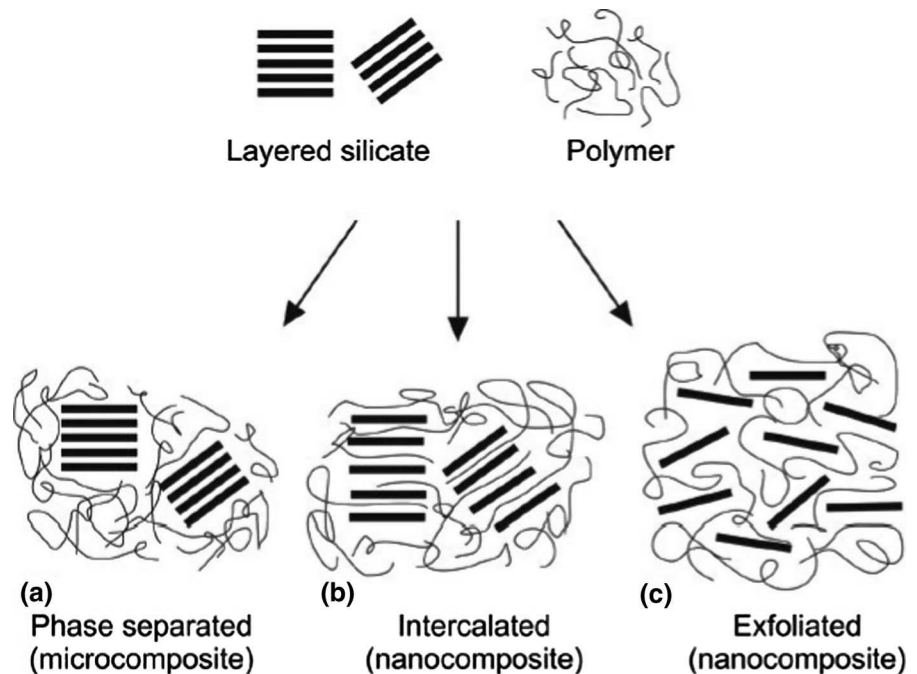
In last two decades, a new and an emerging class of clay filled polymers, called PCNs, has been developed and much research activity has been dedicated to the development of PCNs that could improve the

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 naphthalate (Kim et al. 2008), polyvinyl alcohol (Chen and Evans 2005), polypropylene (Prashantha et al. 2009) and a PA (Zeng et al. 2006). Silica NPs ( $n\text{SiO}_2$ ) have been reported to improve tensile properties of polypropylene (Vladimirov 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 (Vladimirov et al. 2006). Jia et al. (2007) prepared nanocomposites of polyvinyl alcohol with  $n\text{SiO}_2$  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  $n\text{SiO}_2$  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 microscale 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  $\text{Ag}^+$  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 Müntstedt 2005; and this leads us to believe that released  $\text{Ag}^+$  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  $\text{Ag}^+$  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 ( $\text{TiO}_2$ ) is widely used as a photocatalytic disinfecting material for surface coatings (Fujishima et al. 2000).  $\text{TiO}_2$  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  $\text{TiO}_2$  powder-coated packaging film able to reduce *E. coli* contamination on food surfaces. Gelover et al. (2006) demonstrated the efficacy of  $\text{TiO}_2$ -coated films exposed to sunlight to inactivate faecal coliforms in water. Metal doping improves visible light absorbance of  $\text{TiO}_2$  (Anpo et al. 2001), and increases its photocatalytic activity under UV irradiation (Choi et al. 1994). It has been demonstrated that doping  $\text{TiO}_2$  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  $\text{TiO}_2/\text{Ag}^+$  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.

#### $\text{O}_2$ scavengers

Oxygen ( $\text{O}_2$ ) 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  $\text{O}_2$  includes food spoilage by aerobic microorganisms. The incorporation of  $\text{O}_2$  scavengers into food packaging systems can maintain very low  $\text{O}_2$  levels, which is useful for several applications. Oxygen scavenger films were successfully developed by Xiao-e et al. (2004) by adding  $\text{TiO}_2$  NPs to different polymers. The nanocomposite materials could be used as packaging films for a variety of oxygen-sensitive food products. Since  $\text{TiO}_2$  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<sub>2</sub> 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<sup>®</sup> 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  $\pi$  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<sub>2</sub> sensors

There has been an increasing consensus in assuring complete absence of O<sub>2</sub> in oxygen-free food packaging systems and to this effect there is an interest to develop non-toxic and irreversible O<sub>2</sub> sensors with packaging done under vacuum or nitrogen. Lee et al. (2005) developed an UV-activated colorimetric O<sub>2</sub> indicator which uses TiO<sub>2</sub> 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<sub>2</sub> exposure (Gutiérrez-Tauste et al. 2007). Mills and Hazafy (2009) used nanocrystalline SnO<sub>2</sub> as a photosensitizer in a colorimetric O<sub>2</sub> 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<sub>2</sub>NPs. The colour of the films varied according to O<sub>2</sub> 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 <sub>2</sub> 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	<p>Polymeric micelles: shell with amphiphilic block copolymers, core with hydrophobic region with nanoencapsulated lipids, flavouring agents, antibacterial agents, vitamins and antioxidant agents</p> <p>Polymeric nanospheres are solid colloidal particles in which compounds are dissolved, entrapped, encapsulated, chemically bound, or adsorbed to the polymer matrix</p> <p>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</p>	<p>Wu et al. (2012)</p> <p>Garcia-Castello et al. (2010)</p> <p>Letchford and Burt (2007), Flanagan and Singh (2006)</p>
3	Lipid-based nanostructures	<p>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</p> <p>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)</p> <p>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</p>	<p>Mozafari et al. (2006), Taylor et al. (2005), Jesorka and Orwar (2008), Mozafari et al. (2008)</p> <p>Patel et al. (2000), Omri et al. (2003)</p> <p>Mozafari et al. (2006), Zarif (2003), Chaudhry et al. (2008)</p>

**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 $\beta$ -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 <i>Escherichia coli</i> 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), $\alpha$ -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 <sub>2</sub> (E551), magnesium oxide (E530) and TiO <sub>2</sub> 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 $\omega$ -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, <i>Escherichia coli</i>	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 <sup>®</sup> from Aquanova <sup>®</sup> 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, $\beta$ -carotene, lutein, $\omega$ -3 fatty acids, CoQ10). An increase in bioactive bioavailability with Novasol <sup>®</sup> has also been claimed	Carla et al. (2013), Bugusu et al. (2011)
		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 <sup>™</sup> 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)
		$\alpha$ -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 <sup>TM</sup> , from RBC Life Sciences <sup>®</sup> 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 $\beta$ -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-Urbe 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 <sup>®</sup> 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	<p>Nanobiorecognition: it is the conjugation of biomolecules with nanomaterials for the detection of contamination and infectious diseases</p> <p>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</p> <p>Immobilized oligonucleotide probes to magnetic NPs have been used to detect the contamination with <i>Listeria monocytogenes</i> cells of 10 CFU/mL in milk samples. However, this detection included a PCR reaction that confirmed a dose-dependent inhibitory effect</p> <p>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</p> <p>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</p> <p>Functionalized single-walled CNT with multivalent carbohydrate ligands on their surface used for an efficient capture/detection of pathogenic <i>E. coli</i> cells</p> <p>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 <math>1.1 \times 10^3</math>–<math>2.5 \times 10^7</math> CFU/mL within 1 h)</p>	<p>Tallury et al. (2010)</p> <p>Brody et al. (2008)</p> <p>Amagliani et al. (2006)</p> <p>Brody et al. (2008)</p> <p>Scampicchio et al. (2008)</p> <p>Gu et al. (2008)</p> <p>Wang et al. (2012)</p>
8	Food packaging	<p>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</p> <p>Nanostructured aluminium platelets have been self-assembled into wagon-wheel (nano-wheel) structures in order to improve barrier and mechanical properties of plastics</p>	<p>Jun et al. (2007), Motlagh et al. (2012)</p> <p>Mössinger et al. (2007)</p>

**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 <i>Micrococcus lysodeikticus</i> 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'.**

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