Current and projected applications of nanotechnology in the food sector

Aplicações atuais e futuras da nanotecnologia no setor alimentício

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ABSTRACT

GREINER, R. Current and projected applications of nanotechnology in the food sector. *Nutrire:* rev. Soc. Bras. Alim. Nutr. = J. Brazilian Soc. Food Nutr., São Paulo, SP, v. 34, n. 1, p. 243-260, abr. 2009.

The prospects for applications of nanotechnology to the food sector have become more apparent over the last few years. Nanotechnology applications are expected to bring changes to the food sector, including improved production and processing techniques, improved food contact materials, modification of taste, texture and sensation, monitoring food quality and freshness, reduced fat content, enhanced nutrient absorption, and improved traceability and security of food products. A variety of food ingredients, additives, encapsulation systems and food contact materials is already available in some countries and the market for nanotechnology-derived food products and food contact materials is expected to grow worldwide. However, no clear information about the actual use of nanotechnology in the food industry is available and data on the benefits, improvements and risks of nanotechnology applications in the food sector as well as their economical competitiveness are still almost lacking.

Keywords: Nanotechnology. Encapsulation. Engineered nanomaterial. Food. Food contact material. Food packaging. Nanosensors.

RESUMEN

Las posibilidades de aplicación de la nanotecnología al sector de alimentos se tornaron más evidentes en los últimos años. Se espera que su empleo introduzca cambios en el sector de alimentos, incluyendo aumentos de productividad; perfeccionamiento de los procesos; mejora de los materiales de contacto con alimentos; modificaciones de sabor, textura y sensación; vigilancia de la calidad y el frescor; reducción del contenido de grasa; aumento de la absorción de nutrientes y perfeccionamiento de la trazabilidad y seguridad de los productos alimenticios. Una variedad de ingredientes de alimentos, aditivos, sistemas de encapsulación y materiales de contacto con los alimentos ya están disponibles en algunos países y se espera que el mercado de productos alimenticios con origen en la nanotecnología aumente en todo el mundo. Sin embargo, no existe en el momento información sobre como la nanotecnología esta siendo usada en la industria de alimentos, ni datos sobre los beneficios, progresos y riesgos de su aplicación al sector de alimentos o de la competitividad económica de esta tecnología.

Palabras clave: Nanotecnología. Encapsulación. Ingeniería de Nanomateriales. Alimentos. Materiales de contacto con los alimentos. Envases de Alimentos. Nanosensores.

RESUMO

As perspectivas de aplicações da nanotecnologia ao setor alimentício se tornaram mais aparentes nos últimos anos. Espera-se que as aplicações da nanotecnologia trarão mudanças ao setor, incluindo técnicas aperfeiçoadas de produção e processamento, materiais que têm contato com o alimento melhorados, modificação de sabor, textura e sensação, monitoria da qualidade e frescor dos alimentos, reduzido teor de gordura, absorção de nutrientes aumentada, e melhor rastreabilidade e segurança dos produtos alimentícios. Uma variedade de ingredientes, aditivos, sistemas de encapsulação e materiais que entram em contato com o alimento já estão disponíveis em alguns países e espera-se que o mercado para produtos alimentícios derivados da nanotecnologia e materiais que entram em contato com os alimentos cresça mundialmente. Entretanto, não há claras informações disponíveis sobre o real uso da nanotecnologia na indústria de alimentos e dados sobre os benefícios, melhorias e riscos da aplicação da nanotecnologia na indústria de alimentos, bem como sua competitividade econômica ainda são quase ausentes.

Palavras-chave: Nanotecnologia. Encapsulação. Nanomaterial. Alimento. Material de contato com alimento. Embalagem de alimentos. Nanosensores.

INTRODUCTION

The definition of nanotechnology is based on the prefix "nano" which is from the Greek word meaning "dwarf". In more technical terms, the word "nano" means 10^{-9} or one billionth of something. Nanotechnology is a collective term for different, but not always new technologies to design, process and use of materials at the nanometre scale. Even if currently no binding and delimiting definition of nanotechnology exists, the word nanotechnology is generally used when referring to materials with the size of 1 to 100 nanometres in at least one dimension. However, it is also inherent that these materials should display different properties from bulk materials as a result of their small size. These differences include physical, mechanical, electrical, magnetic and optical properties, chemical reactivity and very likely of most concern, toxicity. Generally a change of properties occurs in the order of 100 nm or less, but there are size-related effects that can appear at larger size. At the atomic and molecular level, quantum mechanics is needed; while to describe phenomena and properties and at the everyday scale, Newton's laws, the classical physics, work fine. However, nanomaterials are in a borderline region where either or both approaches may be appropriate. Nanomaterials can be created using a top-down or a bottom-up approach. Top down means to generate nanostructures by starting with a larger piece and caving away material using mechanical, chemical or other form of energy, like creating a sculpture. Bottom-up involves putting together atomic or molecular species via chemical reactions or self-assembly, like building a house. Both approaches can be done in either gas, liquid, supercritical fluids, solid states, or in vacuum. Most of the manufacturers are interested in the ability to control particle size, particle shape, size distribution, particle composition, and degree of particle agglomeration.

Nanotechnology is a broad interdisciplinary area of research, development and industrial activity which is expected to impact almost all areas of daily life. Since the 1980's electronics has been a leading commercial driver for nanotechnology R&D, but other areas including materials, biotechnology and energy are of significant and growing importance. Products of nanotechnology are already on the market. Examples include antibacterial textiles, transparent sunscreens, stain-, water- and odour-repellent fabrics, scratch-free paints for cars, dirt-repellent coatings, self-cleaning windows, bouncier tennis balls, and tennis rackets with a greater stiffness. Some other products of nanotechnology have been around for a very long time. Hieroglyphs on papyrus have been found to have been written with inks containing nanoparticles of soot, gold nanoparticles were used in stained glass windows as far back as the 10th century to obtain a red colour, silver nanoparticles can be found in photographic films and carbon nanoparticles in black tires.

NANOTECHNOLOGY AND THE FOOD INDUSTRY

Many of the world's largest food companies are reported to support specific research programmes to explore the potential of nanotechnology for use in the food sector (CIENTIFICA; REPORT, 2006). It has been suggested that the number of companies currently applying nanotechnologies to food could be as high as 400 and that this number is expected to increase dramatically in the near future (CIENTIFICA; REPORT, 2006). The market for nanotechnology-derived products for the food sector is predicted to grow rapidly in the coming years. A report by Helmut Kaiser Consultancy has estimated that applications of nanotechnology in the food sector would reach US$ 20.4 billion by 2010 (HELMUT KAISER CONSULTANCY, 2004). Another recent report by the consulting firm Cientifica (2006) came up with very different estimates. The report predicted that by 2012 the overall market value of nanotechnology applications in the food sector would reach US$ 5.8 billion. The difference in estimates reflects the difficulty in obtaining the exact information by the food industry about current and planned activities in food nanotechnology. Furthermore, the lacking of a binding and delimiting definition of nanotechnology generates uncertainties in the assignment of a process or material to nanotechnology. Research activities on applications of nanotechnology in the food sector already include development of improved taste, colour, flavour, texture and consistency of food products, increased absorption and bioavailability of nutrients and bioactive compounds, improved quality, shelf-life and safety of food products due to new food packaging materials with improved mechanical, barrier and antimicrobial properties, and nanosensors for traceability and monitoring the condition of food during transport and storage. Broadly, the following categories of nanotechnology applications in the food sector have been identified (CHAUDHRY et al., 2008):

- The use of nanotechnology processes or materials to develop food contact materials. This category includes nanofilters, material for food packaging and coatings for kitchen utensils, processing equipment, and food containers.
- Nano-sized, nano-encapsulated or engineered nanoparticle ingredients including bioactive compounds, nutrients, additives and processing aids.
- Food ingredients that have been processed or formulated to form nanostructures and nanotextures for example to alter taste, texture, and consistency of food products.
- Biosensors for monitoring conditions of food during storage and transportation including packaging with integrated indicators.

Currently many nanotechnology applications in the food sector are at R&D or near-market stages (CIENTIFICA; REPORT, 2006). Only nanotechnology-derived materials for food packaging to improve mechanical and barrier properties and some delivery systems for biologically active compounds are available in some countries.

FOOD CONTACT MATERIALS

A range of food contact materials is already developed or is currently under development. Coatings containing nanoparticles are used to create antimicrobial, scratch-resistant, anti-reflective or corrosion-resistant surfaces. Examples of food contact materials with nano-coatings include kitchen and tableware, equipment used in food processing and food packaging systems. In addition, nanotechnology offers advantages in packaging and storage of food and beverages by increasing the barrier properties of packaging systems for moisture, oxygen, and carbon dioxide, and by improving their mechanical and heat-resistance properties. The nanostructured materials will be either confined in the matrix of the packaging material or it may form a nanolayer on its surface. Finally, nanofilters are being developed for use in the manufacture of food products as well as to replace chemicals and much more complex and expensive devices for filtering for example water.

Food packaging

Chaudhry et al. (2008) have identified food packaging materials as the largest category of current nanotechnology applications for the food sector. The main applications in the area of food packaging systems were reported to be:

- Nanostructured materials to improve packaging properties such as gas and moisture barrier properties, as well as mechanical and heat-resistance properties.
- "Active" food packaging incorporating nanoparticles with antimicrobial or oxygen scavenging properties.
- Biodegradable polymer-nanomaterial composites.
- "Intelligent" food packaging incorporating nanosensors or indicators to monitor and report the condition of the food.

Nanocomposites are prepared by dispersing nanoparticles into a host polymer, generally at less than 5% (w/w) levels. Due to the relatively low levels of nanoparticles needed to achieve the desired properties of the food packaging materials, they do not change their density, transparency and processing characteristics (LEI; HOA; TON-THAT, 2006). Polymer composites incorporating clay nanoparticles were among the first nanocomposites to be developed as improved food packaging materials. Nanoclay-polymer composites have been made from polyamides, nylons, starch, polyolefins, polylactide, polystyrene, ethylene-vinylacetate copolymer, epoxy resins, polyurethane, polyimides and polyethyleneterephthalate. With surface dimensions extending to 1000 nanometres, the tightly bound structure of the nanoclay in a polymer matrix restricts the permeation of gases and liquids (AKBARI; GHOMASHCHI; AROUJALIAN, 2006; ALEXANDRA; DUBOIS, 2000; KE; YONGPING, 2005; XU et al., 2006). Furthermore, the nanoclay-polymer composites demonstrate enhanced fire resistance (RAY et al., 2002), thermal properties (ALEXANDRA; DUBOIS, 2000; KOTSILKOVA; PETKOVA; PELOVSKJ, 2001) and durability (WANG; KOO; CHUNG, 2003). The essential nanoclay raw material is montmorillonite, which is a widely available natural clay commonly derived from volcanic ash/rocks. Potential applications of nanoclay–polymer composites include packaging applications for a variety of foods, such as processed meats, cheese, confectionery, cereals, boil-in-the-bag foods, as well as in extrusion-coating applications for fruit juices and dairy products, or co-extrusion processes for the manufacture of bottles for beer and carbonated drinks (AKBARI; GHOMASHCHI; AROUJALIAN, 2006).

Bayer AG (Germany) developed a nanoclay-polyamide composite film named Durethan® KU 2-2601 with reduced gas and moisture permeation as well as enhanced gloss and stiffness (BAYER, 2003). Durethan® KU 2-2601 unites the advantages of polyamide 6 and ethylene-vinylalcohol copolymer, two common plastics. It is inexpensive but exhibits very good barrier properties, not as good as ethylene-vinylalcohol copolymer, but much better than simple polyamide 6. The embedded nanoclay particles increase the distance the gas molecules have to travel on their way through a film, because gas molecules literally have to zigzag around the silicate plates. This effect is so strong that it cuts the permeability of the film by half compared to conventional polyamides and improves the shelf-life of the content. A further nanocomposite containing clay nanoparticles, named Imperm®, was developed by Nanocor® Inc. (USA) (MAUL, 2005). This material could be used in multi-layer PET bottles for beverages to minimise the loss of carbon dioxide from the drinks and the ingress of oxygen into the bottles, thus keeping beverages fresher and extending shelf-life. In addition, the resultant bottles are both lighter and stronger than glass and are less likely to shatter. Miller Brewing Co. (USA) is reported to use this technology in their beer bottles giving their beer up to a six-month shelf-life. Other Imperm® applications that are being evaluated are multi-layer PET bottles for other alcoholic drinks and carbonated soft-drinks, multi-layer thermoformed containers for deli meats and cheeses and flexible multi-layer films for potato chips and ketchup (FRIENDS OF THE EARTH, 2008). Honeywell Specialty Polymers (USA) has also successfully developed a polymerized nanocomposite film, named Aegis® OX (CHAUDHRY et al., 2008). Aegis® OX is an oxygen-scavenging barrier resin formulated for use in co-injection PET bottle applications. The resins are a blend of active and passive nylon using oxygen scavengers and passive nanocomposite clay particles to enhance the barrier properties for retaining carbon dioxide and keeping oxygen out. This technology has been used since late 2003 in the 2.6-litre Hite Pitcher beer bottle from Hite Brewery Co. (South Korea) and results in an extended shelf-life of the beer of up to 26 weeks (JOSEPH; MORRISON, 2006). In addition to the above mentioned products, the following five nanocomposite barrier products are currently reported to be commercially available (MAUL, 2005): NycoNano™ (NYCOA, USA), Nanoblend™ (PolyOne, USA), Nanomide™ (Nanopolymer Composites Corporation, Taiwan), Systemer (Showa Denko, Japan), Ecobesta® (Ube Industries Ltd., Japan). All these products are nanoclay-polyamide 6 composites. A further area of application is the use of nanoparticles of pigments such as titanium dioxide and zinc oxide as UV absorbers in packaging materials and containers (CHAUDHRY et al., 2008). Titanium dioxide becomes transparent on nanoscale, but retains its UV absorption characteristics. This suggests applications in transparent wraps, films or containers made of plastics such as polystyrene, polyethylene and polyvinylchloride where UV degradation needs to be avoided.

Besides nanocomposite barrier products, food packaging with antimicrobial properties, so called "active" packaging, are currently available. These materials are claimed to preserve the food products by inhibiting the growth of microorganisms. The antimicrobial property of silver has been known for thousands of years and the extremely small size of silver nanoparticles even increases their antimicrobial efficiency. Packaging material incorporating silver nanoparticles are reported to be commercially available (BUND, 2008). Examples include nano-silver food storage containers (Sharper Image®, USA; A-DO Global, China; BlueMoonGoods, USA; Everin, United Kingdom; JR Nanotech Plc., United Kingdom) and nano-silver plastic bags (Sharper Image®, USA; OneWorld, United Kingdom). In addition, nanoparticles of magnesium oxide and zinc oxide have been determined to be highly effective in destroying microorganisms (FOOD PRODUCTION DAILY, 2005). As these would be much cheaper to manufacture as silver nanoparticles, this could have tremendous applications in food packaging (JOSEPH; MORRISON, 2006). SongSing Nanotechnology Co. Ltd. (Taiwan) for example produces a film (Nano Plastic Wrap) containing a nano-zinc oxide based light catalyst, claimed to sterilize in indoor lighting (FRIEND OF THE EARTH, 2008). Furthermore, other types of nanomaterials such as silicon dioxide can be incorporated to develop active packaging that can absorb oxygen and therefore avoid food deterioration. Polymer nanocomposites incorporating silicon dioxide nanoparticles have also been developed for abrasion resistance and packaging materials incorporating titanium nitride nanoparticles, carbon nanotubes or nanofibres for mechanical strength (SORRENTINO; GORRASI; VITTORIA, 2007). In addition, a multi-walled carbon nanotube-polyamide 6 composite was reported to have a better processability due to lower viscosity (SCHARTEL et al., 2005). Last but not least, dirt-repellent plastic bags would be a remarkable improvement in ensuring the safety and security of packaged food.

To improve recycling properties of packaging material, there is an emerging area of R&D into the potential application of biodegradable nanostructured polymers. Like conventional packaging, biodegradable packaging must serve a number of important functions, including containment and protection of food, maintaining its sensory quality and safety, and communicating information to consumers (ROBERTSON, 1993). Unfortunately, so far the use of biodegradable films for food packaging has been strongly limited because of the poor barrier properties and weak mechanical properties shown by natural polymers. The application of nanocomposites promises to expand the use of biodegradable as well as edible films (LAGARÓN et al., 2005; SINHA RAY; BOUSMINA, 2005). It will help to reduce the packaging waste associated with processed foods and will support the preservation of fresh foods, extending their shelf-life (LABUZA; BREENE, 1988; VERMEIREN et al., 1999). Biodegradable plastics are polymeric materials in which at least one step in the degradation process is through metabolism in the presence of naturally occurring organisms without generation of toxic or environmentally harmful residues (CHANDRA; RUSTGI, 1998). Biodegradable polymers include polymers that are directly extracted or removed from biomass such as polysaccharides, proteins, polypeptides and polynucleotides; polymers produced by classical chemical synthesis using renewable bio-based monomers or mixed sources of biomass and petroleum such as polylactide or bio-polyester; and polymers produced by microorganisms or genetically modified bacteria such as polyhydroxybutyrate, bacterial cellulose, xanthan, curdian and pullan. The application of nanotechnology to these polymers may open new possibilities for improving not only the properties but also at the same time the cost-price efficiency. So far, the most studied biodegradable nanocomposites suitable for packaging applications are starch and derivatives, polylactide, poly (butylene succinate), polyhydroxybutyrate, and aliphatic polyesters as polycaprolactone. For example, biodegradable-starch based polymers have poor moisture barrier properties due to their hydrophilic nature, and inferior mechanical properties compared to plastic films. The incorporation of clay nanoparticles in starch polymers has been reported to improve moisture barrier and mechanical properties (AVELLA et al., 2005; CHEN; EVANS, 2005; DE CARVALHO; CURVELO; AGNELLI, 2001; MCGLASHAN; HALLEY, 2003; PARK et al., 2002; PARK et al., 2003). Similarly, polylactide is a biodegradable thermoplastic polymer that has a high mechanical strength, but low thermal stability and low moisture and gas barrier properties compared to plastic polymers. Incorporation of clay nanoparticles into polylactide has been reported to improve tensile modulus and yield strength, and to reduce permeability to oxygen (AKBARI; GHOMASHCHI; AROUJALIAN, 2006).

To ensure food safety, packaging materials incorporating nanostructured indicators, nanosensors, antigen-detecting biosensors or DNA-based biochips are being developed. The key to low-cost, disposable electronic packaging systems will be the development of printing fluids and high-speed printing processes capable of generating low-cost devices that can generate power, sense the environment, amplify signals, process data and drive displays (BUTLER, 2006). When available, the embedded sensors in a packaging film will be able to detect pesticides, allergens, toxins, food-borne pathogens and food-spoilage organisms and trigger a colour change to alert the consumer about these facts. For example, a so-called ''Electronic Tongue'' consists of an array of nanosensors which are extremely sensitive to gases released by food as it spoils, causing a sensor strip to change colour as a result which gives a clear visible signal whether the food is fresh or not (GARLAND, 2004). To be incorporated directly into packaging, the sensors need to be made from cheap and flexible materials. Electrically conductive polymers moulded into sensors with nanoscale features are claimed to detect extremely faint molecular signals of, for example, spoilage bacteria or food-borne pathogens. Such sensors could render obsolete these vague, and frequently inaccurate "best before" dates printed on many food packages. There is also currently research on "smart" packaging that could detect chemical or bacterial contamination and react to combat contamination. These "intelligent" packaging systems release, for example, a preservative if food begins to spoil (ETC GROUP, 2004). Furthermore, indicators, applied for example as labels, printing inks or coatings, add an intelligent function to food packaging in terms of ensuring the integrity of the packaging through detection of leaks or indications of time-temperature variations (ELAMIN, 2006; SMOLANDER et al., 2004; YAM; TAKHISTOV; MILTZ, 2005). Nanoscale-sensing devices are also under development that, when attached to food products and packaging, would act as electronic barcodes (GARLAND, 2004). They would emit a signal that would allow food to be traced from field or farm to factory to supermarket and beyond. Among the near-market developments are nanomaterial-based next-generation packaging displays that include Radio Frequency Identification Display (RFID). The technology consists of microprocessors and an antenna that can transmit data to a wireless receiver. Unlike bar codes, which need to be scanned manually and read individually, RFID tags do not require line-of-sight for reading and it is possible to automatically read hundreds of tags a second. Retailing chains like Wal-Mart (USA), Home Depot (USA), Metro group (Germany), and Tesco (United Kingdom), have already tested this technology (JOSEPH; MORRISON, 2006).

Coatings For Kitchen Utensils And Processing Equipment

Coatings of nanoparticulated forms of metal, metal oxide or a film resin substance with nanoparticles are used to create antimicrobial, scratch-resistant, anti-reflective or corrosion-resistant surfaces. The antimicrobial properties of silver nanoparticles, for example, have been utilised by incorporation into the inner surface of domestic refrigerators (Daewoo, South Korea; Hitachi, Japan; LG Electronics, South Korea; Samsung, South Korea), the surface of cutting boards (A-DO Global, South Korea; Küchenprofi, Germany), baby milk bottles and drinking cups (Baby Dream® Co. Ltd., South Korea), tea pots (SongSing Nanotechnology Co. Ltd., Taiwan), and kitchen and tableware from Nano Care Technology Ltd. (China) (BUND, 2008). Development of nanoscale dirt-repellent coatings for kitchen utensils and food processing equipment is a further area of research. Abattoirs and meat processing plants in particular could benefit from such technology (GARLAND, 2004). Currently, the US based OilFresh Corporation has marketed a new nano-ceramic product as a catalytic anti-oxidant device for use in restaurant deep-frying machines. Unlike other products that simply filter out unwanted oxidation products, the OilFresh nano-ceramic device prevents the oxidation and agglomeration of fats in deep fat fryers due to its large surface area, thus extending the useful life span of the oil and allowing restaurants the flexibility of switching to more healthful vegetable oils. Furthermore, oil use in restaurants and fast food shops could be reduced by half. An additional benefit is that oil heats up more quickly, reducing the energy required for cooking (JOSEPH; MORRISON, 2006). Furthermore, Nano-X (Germany) has developed a black inorganic nanocomposite coating material which greatly improves heat-conducting properties of the cookware, reducing cooking time by up to 30% (Nano-X Information). This black coating material is currently used to modify the surface of aluminium foil and frying pans. Melitta markets the products under the brand names "Toppits® Fix-Brat Alu" and "Toppits® Fix-Grill Pfannen".

Other Food Contact Materials

There is an increasing interest in the application of membrane technology to food processing. Though generally quite similar in terms of membrane chemistry, the nanofiltration membrane allows the diffusion of predominantly monovalent ions such as sodium or chloride as well as water. Larger ionic species, including divalent and multivalent ions and more complex molecules are highly retained. Thus, the technical application of nanofiltration lies between ultrafiltration and reversed osmosis. The global market for nanofiltration membranes increased from US$ 89.1 million in 2006 to an estimated US$ 97.5 million by the end of 2007 and it should reach US$ 310.5 million by 2012 (BCC RESEARCH, 2007). The water treatment sector was projected to account for 72.7% of total revenues in 2007. Besides in water treatment for drinking water production, the main applications of nanofiltration in food production are in the dairy and sugar industry (BARGEMAN; TIMMER; VAN DER HOST, 2005). Around 300,000 m^2 of nanofiltration membranes are assumed to be currently applied in the food industry (VANDEZANDE; GEVERS; VANKELECOM, 2008). In much of the developing world, clean drinking water is hard to come by, and nanotechnology provides one solution. While nanofiltration is also applied to remove turbidity and microorganisms from a water source, it is also commonly used for the desalination of water. In the dairy industry nanofiltration techniques are applied for simultaneous concentration and partial desalination. It is for example crucial in whey processing to maximize removal of monovalent ions while minimizing lactose loss (KELLY; KELLY, 1995). However, nanofiltration is also capable of removing lactose from milk which makes milk and milk-derived products suitable for the lactose-intolerant. A further possible application of nanofiltration in the food industry include lactic acid recovery from fermentation media, colour reduction of food products, removal of toxins from food products, removal of microrganisms and viruses from water and beverages, adjustment of flavour, as well as desalination and concentration of food, dairy and beverage products or by-products. Nanofilters are also capable of separating according to the shape of a molecule rather than its size. Researchers at the University of Nebraska, for example, developed a filter based on silica and cellulose fibres for removal of caffeine (GOHO, 2004). Due to the production process employed, the filter removes specifically caffeine while theophylline, a molecule with a chemical structure almost identical to that of caffeine, was not retained. Thus, this filter could be used to remove caffeine from coffee during brewing without affecting the coffee's flavour compounds. By varying the number of filters, different degrees of decaffeination could be achieved.

NANO-SIZED, NANO-ENCAPSULATED OR ENGINEERED NANOPARTICLE INGREDIENT

A major focus of current nanotechnology applications in food is the development of encapsulation systems for nutrients, bioactive compounds, additives, supplements and processing aids. Nano-encapsulation has emerged as an extension of micro-encapsulation technology that has been used by the food industry for many years. The general approach is to develop nano-sized carriers or nano-sized materials, in order to improve the absorption and, hence, potentially the bioavailability of added materials such as vitamins, phytochemicals, nutrients or minerals (CHEN; WEISS; SHAHIDI, 2006). The materials can be incorporated into solid foods or delivered in beverages without affecting the taste or appearance. Furthermore, nano-encapsulation offers improvements in terms of better protection against for example moisture and oxygen, controlled release of ingredients and supplements, flavour and taste masking, and improved dispersability of ingredients and additives. Nano-encapsulated substances are also being developed as part of interactive foods, which will allow consumers to modify the food depending on their own nutritional needs or tastes.

Protection is needed for many bioactive compounds as they are generally unstable and interact with oxygen or with other food components in the food matrix. Protection may be required from storage to processing to product consumption. Nano-encapsulation can be utilised to isolate active ingredients, nutrients and flavours from other food ingredients, oxygen or moisture. This strategy aims in a reduced destruction of the encapsulated compound during processing and storage and provides a possibility to extend product shelf-life. In addition, the technique provides excellent retention of highly volatile ingredients, such as flavours, over an extended period of time to reduce the flavour loss during the shelf-life of the product (SHEFER; SHEFER, 2005). A key element in nano-encapsulation, however, is the development of nanocapsules that can carry nutrients or bioactive compounds through the stomach into the small intestine without a significant loss of their content. Even live probiotic microorganisms to promote healthy gut function were reported to be encapsulated (HEIDEBACH; FORST; KULOZIK, 2008). Besides protection of the encapsulated compounds from gastric conditions, a higher solubility of hydrophobic food ingredients is achievable by nano-encapsulation. The release of the content from the nanocapsules relies on the encapsulant material, the encapsulated compound and the applied encapsulation technology. The food industry, however, is limited to the use of food-grade ingredients for encapsulation such as food proteins, food carbohydrates, food fats, and food-grade emulsifiers. The release of the encapsulated compounds at the desired site of action in the body is reported to be possible, since release could be triggered by a variety of mechanisms (SANGUANSRI; AUGUSTIN, 2006; SHEFER; SHEFER, 2005). Diffusion processes and degradation of the nanocapsule by digestive enzymes are mechanisms by which release could be controlled. In addition, heat-triggered, moisture-triggered and pH-triggered controlled release is reported in the literature (SHEFER; SHEFER, 2005). Some nanocapsules are temperature sensitive and can be utilised to release active ingredients and flavours at a certain temperature, e.g., upon heating in an oven or microwave oven or upon addition of hot water for hot drinks and soups. Other nanocpasules dissolve in the presence of water or saliva to release the active ingredients or flavours, thereby providing a high impact flavour "burst." Thus, nano-delivery systems can even deliver nutrients and other encapsulated compounds through the mucosal walls in the mouth or nose. Furthermore, nanocapsules can be stable at acidic pH and release their content upon increase of pH value. This pH-triggered release was initially designed to deliver drugs to different regions of the gastrointestinal tract.

A variety of health-food and nutraceutical products based on nano-carrier technology are available worldwide (The Woodrow Wilson Nanotechnology Consumer Products Inventory). Such products are claimed for enhanced absorption and bioavailability in the body. The German company Aquanova® has developed a nanomicelle-based carrier system called NovaSOL® Sustain with a diameter of around 30nm as a new approach to intelligent weight management. Two active substances are encapsulated in one single nano-carrier, coenzyme Q1O to address fat reduction and alpha-lipoic acid for satiety (JOSEPH; MORRISON, 2006). The NovaSOL® technology has also been used to introduce food additives, such as benzoic acid, citric acid, ascorbic acid, dietary supplements and functional food ingredients, such as vitamins A and E, soybean isoflavones, β-carotene, lutein and omega-3 fatty acids in food and beverage products (Aquanova). The delivery system of the company NutraLease Ltd. from Israel is based on “Nano-sized Self-assembled Liquid Structures (NSSL)” technology (NutraLease). The particles are hollow spheres made from fats with a diameter of approximately 30nm. These self-assembled nano-drops are added to the food product and serve as a liquid carrier which allows the entrapped mostly hydrophobic compounds to pass through the stomach effectively without sinking or breaking up. In addition, the NutraLease™ particles allow these compounds to enter the bloodstream from the gut more easily. The technology has already been adopted and marketed by Shemen Industries to deliver Canola Activa oil containing phytosterols, which it claims reduces cholesterol uptake by 14%, by competing for bile solubilisation (NutraLease). In addition, lycopene, β-carotene, lutein, coenzyme Q10 and omega-3 fatty acids have been incorporated into these carriers (JOSEPH; MORRISON, 2006). In addition to NovaSOL® from Aquanova® and NutraLease™ from NutraLease Ltd., NanoCluster™ delivery system for food products from Royal BodyCare Life Sciences® Inc. (USA) and Bioral™ nanocholeate nutrient delivery system for micronutrients and antioxidants are commercially available (CHAUDHRY et al., 2008; JOSEPH; MORRISON, 2006). The NanoCluster™ delivery system is used in a powdered chocolate drink, called Slim Shake chocolate, which is claimed to be sufficiently sweet without added sugar or sweeteners by incorporating cocoa into nanoclusters (RBC Life Sciences). Nanocochleates are 50nm coiled nanoparticles which are reported to protect micronutrients and antioxidants from degradation during manufacture and storage. They can be used to deliver nutrients such as vitamins, lycopene, and omega-3 fatty acids more efficiently to cells, without affecting the colour or taste of food. Furthermore, a great variety of additional nano-sized carrier systems are reported to be under development (CIENTIFICA REPORT, 2006). For example, self-assembled nanotubes from the hydrolysed milk protein α-lactalbumin have been developed recently, which can offer a new naturally derived carrier for nano-encapsulation of nutrients, supplements and pharmaceuticals (GRAVELAND-BIKKER; DE KRUIF, 2006).

Encapsulation has also been used to mask unwanted taste and odour by preventing interaction between the active molecule and the taste receptors in the oral mucosal surface. George Weston Foods, one of the leading bakeries in Western Australia adds nanocapsules containing tuna fish oil high in omega-3 fatty acids to their top selling product Tip-Top® Up™ bread (BUND, 2008). The capsules are designed to break open only when they have reached the stomach, thus avoiding the unpleasant taste of the fish oil. Because tuna fish oil is rich in omega-3 fatty acids which are susceptible to oxidation, encapsulation also extends the shelf-life of food products containing omega-3 fatty acids by protecting the polyunsaturated fatty acids from oxidation. A further type of nano-encapsulation applications is aimed at achieving a uniform dispersal of water-insoluble ingredients including additives in foods and drinks without the addition of extra fat. Also a uniform dispersal of water-soluble ingredients in hydrophobic food products such as oil can be achieved.

There is also a variety of nano-sized food ingredients, supplements and additives currently available. Virtually all of these products claim enhanced absorption and bioavailability of the nano-sized ingredients in the body. BASF produces for example a synthetic form of the tomato carotenoid lycopene, which has a particle size in the range of 100 nm, for addition to soft drinks and other food products (BASF). The addition of water-dispersible lycopene to drinks is not only claimed for certain health benefits, but provides also colour. Furthermore, several nano-based mineral supplements are available. The nano-selenium-enriched Nanotea from Shenzhen Become Industry & Trade Co. Ltd., China (CHAUDHRY et al., 2008) claimed to improve selenium uptake by one order of magnitude and Nano Calcium/Magnesium, Nano Ionic Zinc, and Liquid Nano Particle Size Potassium from Mag-I-Cal.com, USA (Mag-I-Cal.com) as well as SunActive® Fe delivery system from Taiyo, Japan (Taiyo Kagaku) are claimed to provide health benefits by enhancing mineral uptake and bioavailability.

The use of certain inorganic nanomaterials as food additives has also been the subject of patent applications. The most prominent example is a coating intended to provide moisture or oxygen barrier and, thereby, improve shelf-life and/or the flavour impact of confectionery products (MARS INC., 1998). Two further substances which are in focus are the approved food additives silicon dioxide and titanium dioxide. Silicon dioxide is approved as an anti-caking agent in certain food ingredient applications while titanium dioxide is an approved coating agent for certain foods. These additives are used by food manufacturers in the approved formats within the legally permitted scope of application. These substances are also available in nanoscale format. Another example is nano-silver, which is being increasingly marketed as a health supplement. Although no food products containing nano-silver is currently available, the use of colloidal silver formulations in food products is likely to rise in the future. For example, its use as an additive to prepare antibacterial wheat flour has been the subject of a recent patent application (CHAUDHRY et al., 2008).

NANOSTRUCTURES AND NANOTEXTURES

The functionality of many raw materials and the successful processing of food involves the presence, creation and modification of forms of self-assembled nanostructures. For example, setting a gel or adding polymers to delay the sedimentation of dispersions or the creaming of emulsions generally involves creating 3-dimensional nanostructures by causing food biopolymers to assemble into fibrous networks. Foams such as the head on a glass of beer or emulsions like sauces, creams, spreads, yoghurts, butter, margarine, and ice cream are examples of 2-dimensional nanostructures. Creation of a foam requires the production of an air-water interface and creation of an emulsion the production of an oil-water interface. These structures are one-molecule thick and the molecules present at this interface determine interfacial stability. Emulsification and homogenisation as well as processes based on colloidal properties with particle sizes in the nanoscale range have been safely used for decades in food production. Therefore, the use of the term "nanotechnology" for these established technologies might be misinterpreted. However, nanoscience, particularly advances in imaging techniques, will provide insights into food nanostructures, their behaviour and the relationship with macroscopic properties of food. This will allow better selection of raw materials and rational choice for traditional processing methods to be optimised to deliver the desired functionality. Furthermore, in the future more complex multilayer structures can be designed using nanofabrication. Currently nanostructured food ingredients are being developed with the claims that they offer improved taste, texture and consistency (CIENTIFICA REPORT, 2006). Unilever, for example, is developing low-fat ice creams by decreasing the size of emulsion "particles" that give ice cream its texture (Unilever). This strategy is hoped to result in up to 90% less use of the emulsion and thus in a decrease of the fat content of the ice cream from 16% to about 1%. In addition, low-fat nanostructured mayonnaise and spreads are in the pipeline (CHAUDHRY et al., 2008). These products claim to be as ‘‘creamy’’ as their full fat alternatives and, hence, offer a healthier option to the consumer.

BIOSENSORS

Biological molecules such as oligonucleotides, proteins and sugars are claimed to find application as target-recognition groups for nanostructures that could find use, for example, as biosensors in raw materials and food products (CHARYCH et al., 1996). Such biosensors could serve as detectors of food-borne pathogens, spoilage microorganisms, allergens, toxins and other undesirable contaminants and as devices to trade food products. Two projects funded by the European Union, for example, aim in developing diagnostic tools for the food sector (BioFinger, GoodFood). In the "GoodFood Project" a portable array-based nanosensor was developed to detect food-borne pathogens, toxins and other undesired contaminants in raw materials and food products. The device developed in the "BioFinger" project uses cantilever technology, in which the tip of the cantilever is coated with chemicals allowing it to bend and resonate when it binds specific molecules. The "BioFinger" device incorporates the cantilevers on a disposable microchip making it small and portable. Portable devices circumvent the need to send samples to laboratories which is both costly and lengthy, allowing food to be analysed for safety and quality at the farm, abattoir, during transport, processing or at the packaging plant. Improved nanofabrication is likely to lead to new higher density and more efficient and reproducible arrays, and the development of more comprehensive and sophisticated sensors that will be able to detect food-borne pathogens and other contaminants in extremely low concentration in real time. Such technology would have widespread applications in the food industry, especially when considering that current systems can take several days to confirm the presence of pathogens in food.

CONCLUSIONS

Nanotechnology is expected to offer technological advantages in production, processing, storage, transportation, traceability, safety and security of food. However, nanotechnology-derived products need to demonstrate their economical competitiveness prior to commercialisation. Up to now, information concerning the economical competitiveness of nanotechnology-derived products are almost lacking. Food packaging makes up the largest share of the current and short-term predicted market for nanotechnology applications. In addition, several nanotechnology-derived food ingredients, additives and supplements as well as food-contact materials are available in some countries. Furthermore, technologies applying nanoscale materials in filtering and clearing processes for products such as wine, beer and drinking water are being used. However, it is difficult to obtain information by the food industry about current and short-term nanotechnology applications in the food sector. Furthermore, a lot of the currently available information is on more or less realistic aims when applying nanotechnology to food such as, for example, interactive and smart food products. An idea for interactive food is to add nano-encapsulated ingredients or additives to pizza or a colourless and tasteless beverage (CIENTIFICA REPORT, 2006). Selected nanocapsules could be activated by a consumer at a particular microwave frequency, while the others would remain latent, releasing only the preferred flavour, colour or nutrients. Smart food will release nutrients in response to deficiencies detected in the body by nanosensors. The nutrient-containing nanocapsules will be ingested with food, but remain dormant until activated (ETC GROUP, 2004).

Finally, data on risks of nanotechnology applications in the food sector are almost lacking. It is of most concern that nanoparticles make, due to their minute scale, their way deeper into the human body, in ways we do not understand, and producing impacts we have not yet realized and are perhaps currently unable to detect. However, before nano-sized materials find wide-spread application in the food sector, information on potential health risks that may arise from their consumption must be available. There are major gaps in knowledge with regard to the behaviour, fate and effects of nano-sized material via the gastro-intestinal route. It is not known whether nano-sized materials bind to other food components, agglomerate, or remain as free particles in the gastro-intestinal tract. As with other food components interaction of nano-sized materials is very likely to change during passage through the gastro-intestinal tract. Nano-sized material may also affect gut function or gut microflora. An important issue is whether the nano-sized material is differently digested, absorbed and metabolised compared to its macro-scale equivalent. If absorption and bioavailability of the nano-sized form is improved, there might be a need to establish new accepted daily intakes for these materials in the nano-form. Furthermore, nano-sized materials might facilitate uptake of other substances from the intestine. Last but not least almost no information on migration of nanoparticles from food packaging or surfaces used in food storage and processing into food products or beverages is currently available.

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Recebido para publicação em 26/11/08.
Aprovado em 09/02/09.