An overview on properties and usage of nanostructured materials in the food sector

Mohsen Safaei[1,3], Naser Karimi[1,2], Mehran Alavi[1], Mojtaba Taran[1,2], Razieh Rezaei[3*]

[1]*Department of Nanobiotechnology, Faculty of Science, Razi University, Kermanshah, Iran*
[2]*Department of Biology, Faculty of Science, Razi University, Kermanshah, Iran*
[3]*Medical Biology Research Centre, Kermanshah University of Medical Sciences, Kermanshah, Iran*
*Corresponding author Email: rezaei.razieh88@yahoo.com

Abstract
The population growth causes an increasing pressure on food sector so that the problem of malnutrition is a further concern in the today's world. Nanotechnology is one of the new emergent technologies of the present century that would largely influence the world future. Convergence of nanotechnology and food science may lead to emerging abundant potentialities; thus, it is particularly paid attention in the new century. Nanomaterials provides a wide range of applications in producing, storing, packaging, bioavailability, and conductivity of nutrients. On the other hand, scholars and food producers industry mainly concern for the effect of using nanomaterials on the food safety due to unknown features and effects of nanomaterials. Regarding the wonderful potential of applying nanotechnology, a great revolution will be expected in this area. In this review, benefits and health risks of nanomaterial in nutrition and food sciences are highlighted.

Keywords: Nanomaterial, Nanocarriers, Biosensor, Nanofood, Nutraceuticals

1. Introduction

The term of nanotechnology consists of the two parts nano meaning one billionth derived from the Greek word dwarf and technology. To better recognize nano scale it requires probing the world of atoms and molecules [1, 2]. A sugar molecule size is about one nanometer, comparing the ratio of this molecule and an apple is equal to the ratio of an apple to the globe. Nanotechnology as an innovative and practical technology resulted from the convergence of other sciences. In recent decades, it has been considered and increasingly developed so that it referred as the world second industrial revolution. This science, indeed, is the most critical economic potential key in the twenty-first century [3-5]. Nanotechnology manipulates in very small sizes (usually 1-100 nanometers) and can create structures with applied and new characteristics [6]. This technology is a new science branch, which recently initiated to influence other science domains including agriculture, biotechnology, environment, medicine, food and nutrition [7-9].

Regarding lack of food supplies, population growth as well as widespread prevalence of food disorders, it seems necessary to develop food industry. The current challenge is to find a way that, on one hand, it provides essential nutrients for a healthy lifestyle and on the other hand, it provides a sufficient and stable food resource. Nutraceutical is a compound word consisting of the two terms nutrition and pharmaceutics. It generally referred as food components not only characterized by basic nutrition, but also have healthy and valuable biologic activity that prevent or cure diseases. The most important of which are vitamins, carotenoids, anthocyanins, flavonoids, sterols and essential fatty acids [10, 11]. Some of the nutrients are essential to perform vital functions, prevent diseases and maintain health. Using optimized transmission systems for these nutrients improves their absorption. Applying innovative technologies such as nanotechnology in this sector is a new approach that can be considered [12, 13]. As The most important components of nanotechnology in food and beverage industry can be mentioned to nanoparticles, nanocoatings, nanocomposites, nanoporous materials and nanocapsules. Nanotechnology in food domain can be utilized in different areas such as taste, texture, flavor, antimicrobial, attributes, nanosensors for monitoring the quality of food, absorption and bioavailability of nutraceuticals [14-17].

In recent years, nanotechnology turned into a critical element of food industry. However, some of nanotechnology applications are still controversial. Metallic materials, for instance, in particular, silver particles and other nanoparticles largely used in packaging for preventing food spoilage can penetrate food texture, which may threat human health [18, 19]. Food industry, like any other sciences and industries, affected by changes resulted from nanotechnology developments and witnessed great changes in food production, processing, and distribution. This study reviews some of the common applications and studies conducted on applying nanotechnology in the area of nutrition and food industry and mentioned some of the challenges.

2. Nanobiomaterials

Nanomaterial referred to the material with synthetic or natural origin made through nanotechnology. These materials are combination of different sizes with controllable characteristics at nanoscale [20, 21]. Nanobiomaterials are new materials at interact of biomaterials and nanotechnologies, which remove former barriers and finally produce functions with global potential benefits [22]. Nanobiomaterials largely considered as the small size and particular characteristics in different biosciences. One of its functions is applying in food and nutrition discussion including transferring nutrients to the cell and improving its efficiency [23], adding desired color and taste to the food [24], adding nutrients sensitive to the heat and pH, as well as food safety [25, 26].

Different nanomaterials produced and applied in food industry, some of which have characteristics that used for creating new structures and adding desired features to food. Cochleates, for instance, are phospholipid bivalent sediments of natural materials resistant to environmental factors. They also used for encapsulation and transferring many bioactive compounds such as hardly water soluble compounds, proteins, heat and pH sensitive nutrients as well as unfavorable environmental conditions [27]. Effective nutrient transferring system requires encapsulated active compounds method to a given known destination, have an appropriate concentration, be constant over a long period and prevent premature degradation [28]. Nanoparticles are more capable in encapsulating and releasing materials comparing former systems; in particular, due to the small size, they directly enter into circulatory system and improve conductivity [29].

3. Nanocarriers in food and nutrition

Some of the characteristics of a desirable transmission system include: the ability to carry adequate amounts of nutrient and protect it during processing, storing and transporting; the prevention of nutrients decomposition; the ability to combine with nutrient without changing its properties; the lack of stimulation of immune system; the ability of targeted transmission and controlled release, having the economic efficiency to transport nutrients. Nanocarriers can improve absorption of various compounds, so that this technology can be used to improve transmission system of nutrients [30, 31].
Food additive are functional components added to enhance food quality and durability such as drugs, emulsifiers, vitamins, antioxidants, flavors, antimicrobials, colorants, stabilizers, preservatives, etc [32, 33]. Food additives can be used as additives with a carrier such as nanocarriers. Nanocarriers are of nanostructures largely used in nutrition and food industry embracing biopolymers-based nanocarriers and nanostructure lipid carriers (nanocapsules, nanoemulsions, nanoliposomes, nanoniosomes, and solid lipid particles) [34, 35]. Characteristics of these structures, the potential and actual use in food and nutrition industry evaluated as follows (Figure 1).

3.1. Nanoemulsions

Nanoemulsions are the particles in 20-200 nanometer size with proper thermodynamic stability [36]. These particles are transparent solutions produced by two immiscible liquid phases through adding some surfactant; indeed, they are triple systems. Nanoemulsions produced through two methods of low-energy and high-energy emulsification [37]. Membrane emulsification, spontaneous emulsification, solvent substitution, reverse emulsion and reverse phase are of common methods of low-energy nanoemulsions. High-energy emulsification of nanoemulsions produced by mechanical equipment including colloid mills, fast or high-pressure homogenizers and ultrasonic homogenizers [38, 39]. High-energy emulsification method has higher industrial application as controlling the size of emulsion particles and producing adequate and high-varied emulsions [40]. Nanoemulsions considerable applications in food industry included food enrichment, increased water solubility of critical nutrients and vitamins, improved efficiency of the reactions such as interesterification and hydrogenation [41, 42]. Nanoemulsions used for water, milk, beverages, vitamins, minerals and other compounds enrichment, which control functional compounds releasing in formulation and production of functional drinks [43, 44]. Nanoemulsions often release their compounds through activations by heat, pH, sound frequencies, or other stimulants and adjust food color, taste, or nutrient contents according to gustatory or individual's health conditions [15]. Antimicrobial effect of nanoemulsions in decontamination of food equipment, packaging materials and different food materials are other functions of nanoemulsions [45-47].

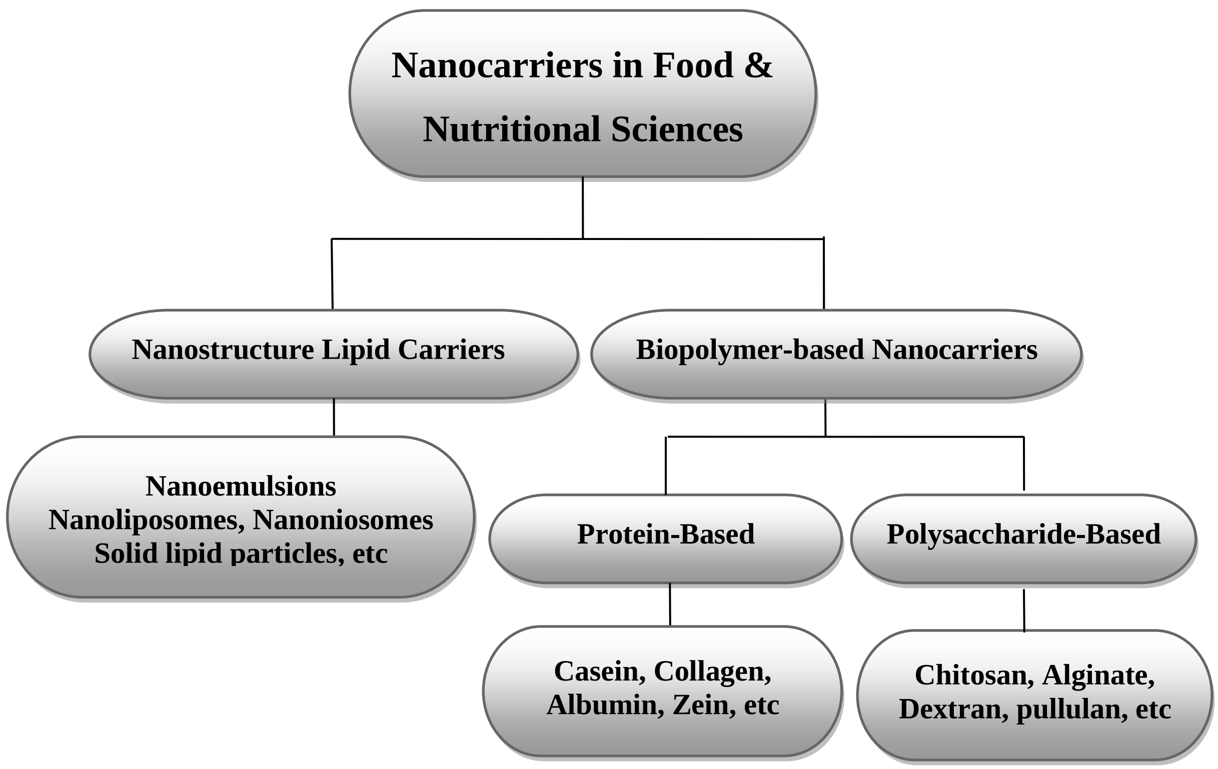

Figure 1. *Nanocarriers in food and nutritional sciences*

3.2. Nanoliposomes

Liposomes are another type of nanostructures used to add functionality to foods. Nanoliposomes are colloidal particles composed of lipid molecules, which accumulate in the form of organized bilayer membranes once react to water. Imposing energy and shear force turns them into sphere [48, 49]. Liposomes can encapsulate hydrophilic active substances inside the membrane and at the surface, and hydrophobic substances between the membranes. Nanoliposomes are contrary to the lipophilic nanoemulsions, which contain and transfer hydrophobic or soluble elements. Further, internal pH is adjustable so that they can contain the elements, which are unstable under special conditions [50, 51]. Liposomes are less interested in food industry due to the easily broken structure.

3.3. Nanoniosomes

Nanoniosomes are used for transferring nutraceutical. Niosomes formed based on nonionic surfactants in aqueous environment enabling to overlap both types of hydrophilic and hydrophobic nutraceutical. Niosomes are structurally similar to liposomes; however, nisomes are more advantageous to liposomes in terms of higher stability, lower final price and biocompatibility as different ingredients [52, 53].

3.4. Solid lipid nanoparticles (SLN)

Solid lipid nanoparticles as nutrient transportation system are different from emulsions, liposomes, and polymeric nanoparticles. SLNs formed by substituting emulsified oil phase (O/W) with solid oil or a mixture of solid oils, meaning a combination of lipid matrix particles turns into solid at room temperature. SLNs formed through 0.1% to 30% solid lipid dispersed in the liquid phase and 0.5 to 5% of surfactants, also used if necessary. SLN size is in the range of 40-1000 nanometers [54, 55]. SLNs used in diet and nutrition as mean of delivering bioactive food components such as isoprenoides, fatty acids, phenolic compounds, proteins/amino acids, polysaccharides, minerals, etc [56].

3.5. Biopolymer nanoparticles

Biopolymer nanoparticles are solid bioactive particles with the diameter of 100 nanometers or less [57]. They are now commonly used in drug delivery, gene transfer [57], anticancer [58] antibacterial [59, 60] and antifungal [61]. Food-grade biopolymers also used to produce nanoparticles. These biopolymer nanoparticles utilized for targeted delivery of nutrients such as vitamins, minerals, and pigments. These materials are also characterized as antimicrobial, which can be used in food packaging industry. However, in general, biopolymer nanoparticles are still limitedly used in nutritional systems [62].

4. Important usage of nanotechnology in food industry

The most important applications of nanotechnology include producing food with the possibility of changing their color, taste and nutrients in accordance with market needs; filters for removing toxins; improving flavors by passing through certain molecules based on the specific shape rather than size of the materials and using special packaging for identifying food spoilage and warning customers through color change. The areas of application of nanotechnology in food and beverage industry, which are currently under investigation, include improving the delivery of medicinal food and bioactive compounds to enhance human health; the flavor of medicinal bioactive compounds; solubility; controlled release and color correction of products; modified bioavailability; preserving the stability of micronutrients and bioactive compounds during the process of storage and distribution (Figure 2).

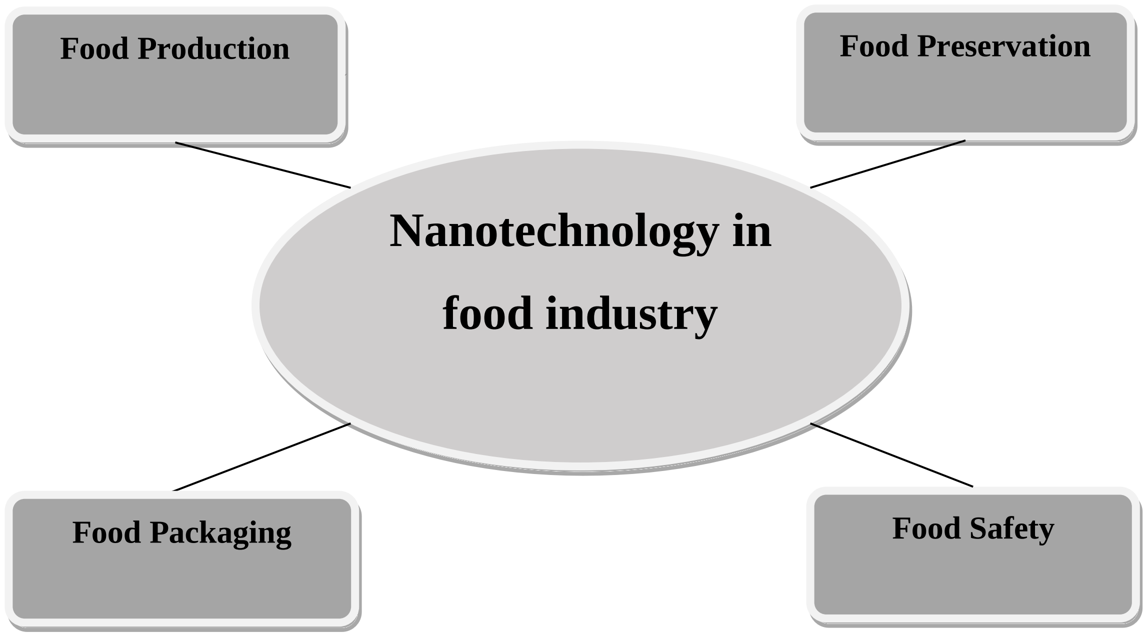

Figure 2. *Important usage of nanotechnology in food industry*

4.1. Food production

In the present competitive environment, factories and companies operating in food industry faced with many problems, like many other industries, in production and selling the products. Consumers seek for the tasty, healthy and high-quality products, which all directly related to production technology [63, 64]. Nowadays, food industry largely competes in technological term; therefore, it is necessary to utilize innovative technologies to develop and maintain the market in food industry and food processing. The future belongs to the processed, new products trying to meet the objectives including improved product performance, longer shelf life, freshness and food safety, that all of them achieved through utilizing nanotechnology [65, 66].

Tiny arrays of food additives can produce novel food groups by synthesizing required nutrients, flavor compounds, etc. In addition, synthesizing nutrients in food groups may change the taste, composition and attain producing new food products in various tastes and colors [67-69]. Nanotechnology also used for treatment of many diseases such as diabetes and obesity so that produce delicious food containing fat substitutes, and prevent fat storage by body; in addition, these foods have no adverse effect on body health [70, 71]. Some materials have high nutritional values that are critical and necessary for body; though, rarely used due to the taste and nutritional habits. Applying nanotechnology can add these materials as food additives and produce enriched foods [25, 72].

Some scholars believe that using molecular engineering, in the future, may provide the possibility of large quantities of foods without soil, seed and field. This technology would eliminate world hunger. Nanomachines in this technology produce the required nutrients by carbon, hydrogen and oxygen atoms existing in water compound or air carbon dioxide rather cultivating the plants and rearing the animals to obtain protein and carbohydrates [73, 74]. Moreover, nanobots in food start moving in circulatory system and remove it from fat and other pathogenic remnants. Molecular food manufacturing considered as one of nanotechnology goals and appeal, which is not immediately achieved. Molecular foods eradicate the hunger, increase nutrients values and remove the risk of allergens in foods [75, 76].

4.2. Food preservation

Nanotechnology is effective in food preservation through three ways of disinfecting the surfaces, protecting of antioxidants and controlling enzymes activities [77]. Disinfecting residues is the critical strategy of fighting against harmful microorganisms [78]. Oxidation occurs in an oxygenated environment and high temperature. Antioxidants play a critical role in neutralizing such oxidation processes [79]. These are primarily the phenols found in most plant-based food products [80]. Therefore, evaluating antioxidant power of food products is a key task in term of food quality control.

4.3. Nanobiosensors for food analysis

Biosensor is a compact analysis device made up of a sensitive biological element closely interacting with a transducer. The diagnosis criterion is based on the specificity of the interaction of the analyte with the biological element [81]. The most common biological elements in biosensors are enzymes, antibodies, cell receptors, tissues and nucleic acids. The transducers used in biosensors include a variety of optical, electrochemical, piezoelectric and thermometers. The variety of nanostructures had been examined to determine the feasibility of their application in nanosensors. Some nanostructures used in nanobiosensors are nanoparticles, quantum dots, carbon nanotube and porous silicon amongst which nanoparticles and carbon nanotubes had been studied more [82]. Biosensors can be classified in terms of their type of biological element, function of transducers and application which are used for different purposes such as quality control and food safety. Biosensors are categorized to optical, magnetic, electrochemical, piezoelectric and thermometric groups based on the mode of signal transmission. The specific binding changes one or more of the physical and chemical properties such as changes in pH, electron transfer, heat transfer, absorbance or release of gases which are measured by the transducer [82, 83].

Foodborne pathogens cause economic loss, human injuries and even death. The diagnosis of pathogeny is well established using different culture techniques, biological tests like ELISA assay to detect and enumerate pathogenic factors in food. Although the use of conventional methods to detect and differentiate various samples may be sensitive and inexpensive, biosensors provide the immediate analysis of sample [84]. In recent years, a variety of biosensors has been developed expedite the process of food quality control by diagnosing the pathogenic factors within some minutes. In this regard, nanotechnology plays a crucial role in the development of biosensors so that the diagnosis limit has been improved to nanoscale [82]. Nanobiosensors with the integration of Nano and Bio technologies by electronic process are designed so that they can only react to a specific material in order to provide precise tracking and analysis devices in microscales by utilizing the power of photoelectron and microelectrodes and specific reaction to a specific substance. Nanobiosensors can be integrated with microbiochips to increase their functionality and performance which, in turn, result in microdevices that are portable, easy to use and cheap. These sensors are considered as useful devices in the diagnosis and control of hazardous contaminants and pathogenic bacteria in water and food products from animals and plants. These sensors provide the possibility of identifying the small amounts of detrimental chemical, viral and bacterial compounds in food system and bring about an outstanding transformation in food quality control [83].

4.4. Food Packaging

Food packaging and monitoring is the major focus of research and development (R&D) sectors in nanotechnology companies related to food industry. Financial perspectives of nanotechnology in packaging industry led to the prosperity of this technology [85, 86]. Some advantages of using nanomaterial in food packaging are higher physical efficacy and biodegradation of the packages, using surface nanocoatings to enhance inhibitory properties, applying nanomaterial with antimicrobial or antioxidant effect on the packaged food, utilizing nanosensors for food quality and safety evaluation [87].

The primary purpose of plastic food packaging is to prevent content drying and protect from moisture and oxygen. Producing enriched plastics packaging of silicate nanoparticles or polymer nanomaterials prolongs direction of moisture, oxygen and other gases entering into packages; therefore, postpones food spoilage [88, 89]. It takes several days for current systems to discover pathogens in food; thus, it seems necessary to find more optimum alternatives. Nanotechnology may be used to faster and easier specify food spoilage. For this reason, portable nanosensors utilized to find hazardous chemicals, pathogens and toxics in food [90, 91]. By doing so, it is no longer need to send food samples to the laboratory to determine products health and quality in farms and slaughterhouses. Applying DNA biochip to detect pathogen is under development. This approach is used for detecting different noxious bacteria of meat, fish, fruits and vegetables [92-94].

Microprocessors that send radio frequencies to wireless receivers can also be used in food packaging for controlling food items from store to the consumer in contrast to the barcodes, which require manual, one-by-one scanning. Radiofrequency identification (RFID) and surface acoustic wave (SAW) labels do not require linear read and large numbers read in one second. The main disadvantage of this method is the high cost of silicone production. Integrating nanotechnology and electronic (nanotronics) make these labels cheaper and more efficient; further, it is also easier to implement [95-97]. This technology, anyway, may have poisoning potential through transferring the toxins from packaging to food. Any chemical transfer must be kept under a given threshold [98]. Nanocomposite is referred to the composites which at least one of its components is in nanoscale. Nanobiocomposites have not only nanoscale compounds but also bioactive compounds which are biodegradable and converts to their microunites by degrader creatures in environment. The variety of nanoparticles used in nanocomposites for food packaging specifies that nanomaterials, used in food packaging are divided into two groups of organic and inorganic materials. Accordingly, inorganic materials include nanoparticles of iron, silver, titanium, calcium, silica, etc. Nanocomposites are biodegradable and ecofriendly compounds which are widely used for food packaging [99, 100].

5. Safety of nanomaterials in food production

Since the dynamic nature of nanomaterials, no general conclusion obtained on the safety of nanotechnology-based foods. In general, using nanoparticles in food packaging is more agreed at the community level comparing direct usage in food structure [101]. Developing nanotechnology in food industry requires attention and policy making in safety issue. The critical point of using nanomaterial is the possibility of toxin effect in the body; whereas, bulk materials lack such effects [102].
Conventional toxicology evaluates and determines materials safety only through three factors of dosage, chemical compositions and exposure; while, many factors considered in investigating nanoparticles safety including physical and chemical characteristics such as nanostructure, shape, agglomeration, aggregation, chemical composition, surface modification, surface charges, purity and impurities. This causes nanomaterials toxicity more difficult than conventional Toxins [103]. Food products containing nanoadditives are now increasing in market; lack of accurate and consistent regulations may increase risks of using these products. Nanoparticles have larger surface and are more reactive, which probably results in higher toxicity [104-106].

References

1. Barth, J.V., Costantini, G. Kern. K.: Engineering atomic and molecular nanostructures at surfaces. Nature 437 (2005) 671–679.
2. Rhodes, C.J.: Eating small: applications and implications for nanotechnology in agriculture and the food industry. Science progress 97 (2014) 173–182.
3. Roco, M.C., Harthorn, B., Guston, D. Shapira, P.: Innovative and responsible governance of nanotechnology for societal development. In Nanotechnology Research Directions for Societal Needs in 2020. Springer Netherlands. 2011, pp. 561–617.
4. Kroto, H.: Nanoscience and nanotechnology in the twenty-first century. Drug delivery and translational research 3 (2013) 297–298.
5. Khan, A.S.: Ethics and nanotechnology. In Ethics in Science, Technology and Engineering, IEEE International Symposium on pp. 1–14.

6. Palombo, M., Deshmukh, M., Myers, D., Gao, J., Szekely, Z. Sinko, P.J.: Pharmaceutical and toxicological properties of engineered nanomaterials for drug delivery. Annual review of pharmacology and toxicology 54 (2014) 581–598.
7. Jha, R.K., Jha, P.K., Chaudhury, K., Rana, S.V. Guha, S.K.: An emerging interface between life science and nanotechnology: present status and prospects of reproductive healthcare aided by nanobiotechnology. Nano reviews 5 (20144) 22762.
8. Sekhon, B.S.: Nanotechnology in agri-food production: an overview. Nanotechnology science and applications 7 (2014) 31–53.
9. Formoso, P.R., Muzzalupo, L., Tavano, G., De Filpo, G. Pasquale Nicoletta F.: Nanotechnology for the Environment and Medicine. Mini reviews in medicinal chemistry 16 (2016) 668–675.
10. Shahidi, F.: Nutraceuticals and functional foods: whole versus processed foods. Trends in food science and technology 20 (2009) 376–387.
11. Sahni, J.K.: Exploring delivery of nutraceuticals using nanotechnology. International journal of pharmaceutical investigation 2 (2012) 53.
12. Schneider, U.A., Havlik, P., Schmid, E., Valin, H., Mosnier, A., Obersteiner, M., Bottcher, H., Skalsky, R., Balkovic, J., Sauer, T. Fritz, S.: Impacts of population growth, economic development, and technical change on global food production and consumption. Agricultural Systems 104 (2011) 204–215.
13. Frewer, L.J., Gupta, N., George, S., Fischer, A.R.H., Giles, E.L. Coles, D.: Consumer attitudes towards nanotechnologies applied to food production. Trends in food science and technology 40 (2014) 211–225.
14. De Azeredo, H.M.: Antimicrobial nanostructures in food packaging. Trends in food science and technology 30 (2013) 56–69.
15. Momin, J.K., Jayakumar, C. Prajapati, J.B.: Potential of nanotechnology in functional foods. Emirates journal of food and agriculture 25 (2013) 10–19.
16. Lu, J. Bowles, M.: Improving the food safety in supply chain: the value of nanotechnology on a growing problem. Quality assurance and safety of crops and foods 6 (2014) 123–133.
17. Yao, M., McClements, D.J. Xiao, H.: Improving oral bioavailability of nutraceuticals by engineered nanoparticle-based delivery systems. Current opinion in food science 2 (2015) 14–19.
18. Martinez-Abad, A., Lagaron, J.M. Ocio, M.J.: Development and characterization of silver-based antimicrobial ethylene–vinyl alcohol copolymer (EVOH) films for food packaging applications. Journal of agricultural and food chemistry 60 (2012) 5350–5359.
19. Youssef, A.M., Abdel-Aziz, M.S. El-Sayed, S.M.: Chitosan nanocomposite films based on Ag-NP and Au-NP biosynthesis by Bacillus Subtilis as packaging materials. International journal of biological macromolecules 69 (2014) 185–191.
20. Kreyling, W.G., Semmler-Behnke, M. Chaudhry, Q.: A complementary definition of nanomaterial. Nano today 5 (2010) 165–168.
21. Hochella, M.F., Spencer, M.G. Jones, K.L.: Nanotechnology: nature's gift or scientists brainchild. Environmental science: Nano 2 (2015) 114–119.
22. An, J., Chua, C.K., Yu, T., Li, H. Tan, L.P.: Advanced nanobiomaterial strategies for the development of organized tissue engineering constructs. Nanomedicine 8 (2013) 591–602.

23. Barar, J.: Cellular trafficking and subcellular interactions of cationic gene delivery nanomaterials. Journal of pharmacy and nutrition sciences 1 (2011) 68–81.
24. Anandharamakrishnan, C.: Nanoencapsulation of food bioactive compounds. In techniques for nanoencapsulation of food ingredients. Springer New York, 2014, pp. 1–6.
25. Kaya-Celiker, H. Mallikarjunan, K.: Better nutrients and therapeutics delivery in food through nanotechnology. Food engineering reviews 4 (2012) 114–123.
26. Weidemaier, K., Carruthers, E., Curry, A., Kuroda, M., Fallows, E., Thomas, J., Sherman, D. Muldoon, M.: Real-time pathogen monitoring during enrichment: a novel nanotechnology-based approach to food safety testing. International journal of food microbiology 198 (2015) 19–27.
27. Padua, G.W. Wang, Q.: Nanotechnology research methods for food and bioproducts. John Wiley & Sons, 2012.
28. Acosta, E.: Bioavailability of nanoparticles in nutrient and nutraceutical delivery. Current opinion in colloid and interface science 14 (2009) 3–15.
29. Skirtach, A.G., Dejugnat, C., Braun, D., Susha, A.S., Rogach, A.L., Parak, W.J., Mohwald, H. Sukhorukov, G.B.: The role of metal nanoparticles in remote release of encapsulated materials. Nano letters 5 (2005) 1371–1377.
30. Chen, L., Remondetto, G.E. Subirade, M.: Food protein-based materials as nutraceutical delivery systems. Trends in food science and technology 17 (2006) 272–283.
31. McClements, D.J., Decker, E.A., Park, Y. Weiss, J.: Structural design principles for delivery of bioactive components in nutraceuticals and functional foods. Critical reviews in food science and nutrition 49 (2009) 577–606.
32. Canham, L.T.: Nanoscale semiconducting silicon as a nutritional food additive. Nanotechnology 18, 185704.
33. Wang, Y., Tang, F., Xia, J., Yu, T., Wang, J., Azhati, R. Zheng, X.D.: A combination of marine yeast and food additive enhances preventive effects on postharvest decay of jujubes (Zizyphusjujuba). Food chemistry 125 (2011) 835–840.
34. Fathi, M., Mozafari, M.R. Mohebbi, M.: Nanoencapsulation of food ingredients using lipid based delivery systems. Trends in food science and technology 23 (2012) 13–27.
35. Joye, I.J. McClements, D.J.: Biopolymer-based nanoparticles and microparticles: fabrication, characterization, and application. Current opinion in colloid and interface science 19 (2014) 417–427.
36. Delmas, T., Piraux, H., Couffin, A.C., Texier, I., Vinet, F., Poulin, P., Cates, M.E. Bibette, J.: How to prepare and stabilize very small nanoemulsions. Langmuir 27 (2011) 1683–1692.
37. Yang, Y., Marshall-Breton, C., Leser, M.E., Sher, A.A. McClements, D.J.: Fabrication of ultrafine edible emulsions: Comparison of high-energy and low-energy homogenization methods. Food hydrocolloids 29 (2012) 398–406.
38. Date, A.A., Desai, N., Dixit, R. Nagarsenker, M.: Self-nanoemulsifying drug delivery systems: formulation insights, applications and advances. Nanomedicine 5 (2010) 1595–1616.
39. Jaiswal, M., Dudhe, R. Sharma, P.K.: Nanoemulsion: an advanced mode of drug delivery system. 3 Biotech 5 (2015) 123–127.

40. Liang, X.J.: Nanopharmaceutics: the potential application of nanomaterials, World Scientific, 2013.
41. Qian, C., Decker, E.A., Xiao, H. McClements, D.J.: Physical and chemical stability of β-carotene-enriched nanoemulsions: Influence of pH, ionic strength, temperature, and emulsifier type. Food chemistry 132 (2012) 1221–1229.
42. Saberi, A.H., Fang, Y. McClements, D.J.: Fabrication of vitamin E-enriched nanoemulsions by spontaneous emulsification: Effect of propylene glycol and ethanol on formation, stability, and properties. Food research international 54 (2013) 812–820.
43. Rao, J. McClements, D.J.: Impact of lemon oil composition on formation and stability of model food and beverage emulsions. Food chemistry 134 (2012) 749–757.
44. Lane, K.E., Li, W., Smith, C. Derbyshire, E.: The bioavailability of an omega-3-rich algal oil is improved by nanoemulsion technology using yogurt as a food vehicle. International journal of food science and technology 49 (2014) 1264–1271.
45. Acevedo-Fani, A., Salvia-Trujillo, L., Rojas-Grau, M.A. Martin-Belloso, O.: Edible films from essential-oil-loaded nanoemulsions: Physicochemical characterization and antimicrobial properties. Food hydrocolloids 47 (2015) 168–177.
46. Salvia-Trujillo, L., Rojas-Grau, A., Soliva-Fortuny, R. Martin-Belloso, O.: Physicochemical characterization and antimicrobial activity of food-grade emulsions and nanoemulsions incorporating essential oils. Food hydrocolloids 43 (2015) 547–556.
47. Severino, R., Ferrari, G., Vu, K.D., Donsi, F., Salmieri, S. Lacroix, M.: Antimicrobial effects of modified chitosan based coating containing nanoemulsion of essential oils, modified atmosphere packaging and gamma irradiation against Escherichia coli O157: H7 and Salmonella Typhimurium on green beans. Food control 50 (2015) 215–222.
48. Alavi, M., Karimi, N. Safaei, M.: Application of Various Types of Liposomes in Drug Delivery Systems. Advanced pharmaceutical bulletin 7 (2017) 3–9.
49. Bouarab, L., Maherani, B., Kheirolomoom, A., Hasan, M., Aliakbarian, B., Linder, M. Arab-Tehrany, E.: Influence of lecithin–lipid composition on physico-chemical properties of nanoliposomes loaded with a hydrophobic molecule. Colloids and surfaces B: Biointerfaces 115 (2014) 197–204.
50. Mozafari, M.R., Flanagan, J., Matia-Merino, L., Awati, A., Omri, A., Suntres, Z.E. Singh, H.: Recent trends in the lipid-based nanoencapsulation of antioxidants and their role in foods. Journal of the science of food and agriculture 86 (2006) 2038–2045.
51. Bozzut, G. Molinari, A.: Liposomes as nanomedical devices. International journal of nanomedicine 10 (2015) 975–999.
52. Pardakhty, A. Moazeni, E.: Nano-niosomes in drug, vaccine and gene delivery: a rapid overview. Nanomedicine journal 1 (2013) 1–12.
53. Moghassemi, S. Hadjizadeh, A.: Nano-niosomes as nanoscale drug delivery systems. Journal of controlled release 185 (2014) 22–36.
54. Uner, M. Yener, G.: Importance of solid lipid nanoparticles (SLN) in various administration routes and future perspectives. International journal of nanomedicine 2 (2007) 289–300.

55. Ascenso, A., Margarida Ribeiro, H., Cabral Marques, H. Simoes, S.: Topical delivery of antioxidants. Current drug delivery 8 (2011) 640–660.
56. Weiss, J., Decker, E.A., McClements, D.J., Kristbergsson, K., Helgason, T. Awad, T.: Solid lipid nanoparticles as delivery systems for bioactive food components. Food biophysics 3 (2008) 146–154.
57. Nitta, S.K. Numata, K.: Biopolymer-based nanoparticles for drug/gene delivery and tissue engineering. International journal of molecular sciences 14 (2013) 1629–1654.
58. Asgarshamsi, M., Sadeghi, H., Hasanzadeh, F., Fatahi, A. Varshosaz, J.: Synthesis of chitosan oligomer conjugated methotrexate nanomicells for purpose of co-delivery of anticancer drugs. Research in pharmaceutical sciences 7 (2012) 593.
59. Safaei, M., Taran, M.: Optimal conditions for producing bactericidal sodium hyaluronate-TiO_2 bionanocomposite and its characterization. International Journal of Biological Macromolecules 104 (2017) 449–456.
60. Safaei, M., Taran, M.: Optimized synthesis, characterization, and antibacterial activity of an alginate–cupric oxide bionanocomposite. Journal of Applied Polymer Science 135 (2018) 45682.
61. Safaei, M., Taran, M.: Fabrication, characterization, and antifungal activity of sodium hyaluronate-TiO_2 bionanocomposite against Aspergillus niger. Materials Letters 207 (2017) 113–116.
62. Arroyo-Maya, I.J. McClements, D.J.: Biopolymer nanoparticles as potential delivery systems for anthocyanins: Fabrication and properties. Food research international 69 (2015) 1–8.
63. Azurra, A. Paola, P.: Consumers behaviours and attitudes toward healthy food products: The case of organic and functional foods. Paper presented at the 113th EAAE Seminar: A resilient European food industry and food chain in a challenging world, Chania, Greece.
64. Drewnowski, A.: Healthy diets for a healthy planet. The American journal of clinical nutrition 99 (2014) 1284–1285.
65. Siegrist, M.: Factors influencing public acceptance of innovative food technologies and products. Trends in food science and technology 19 (2008) 603–608.
66. Joe, M.M., Chauhan, P.S., Bradeeba, K., Shagol, C., Sivakumaar, P.K. Sa, T.: Influence of sunflower oil based nanoemulsion (AUSN-4) on the shelf life and quality of Indo-Pacific king mackerel (Scomberomorusguttatus) steaks stored at 20° C. Food control 23 (2012) 564–570.
67. Weis, J., Takhistov, P. McClements, D.J.: Functional materials in food nanotechnology. Journal of food science 71 (2006) 107–116.
68. Chaudhry, Q., Scotter, M., Blackburn, J., Ross, B., Boxall, A., Castle, L., Aitken, R. Watkins, R.: Applications and implications of nanotechnologies for the food sector, Food additives and contaminants 25 (2008) 241–258.
69. Chaudhry, Q. Groves, K.: Nanotechnology applications for food ingredients, additives and supplements. Nanotechnologies in food, Royal society of chemistry, 2010, pp.69–85.
70. Eldaw, A.: Nanotechnology in elevation of the worldwide impact of obesity and obesity-related diseases: potential roles in human health and disease. Journal of diabetes science and technology 5 (2011) 1005–1008.

71. Pereira, D.I.: Medium-chain fatty acid nanoliposomes suppress body fat accumulation in mice. British journal of nutrition 106 (2011) 1319–1320.
72. Zimet, P., Rosenberg, D. Livney, Y.D.: Re-assembled casein micelles and casein nanoparticles as nano-vehicles for ω-3 polyunsaturated fatty acids. Food hydrocolloids 25 (2011) 1270–1276.
73. Scott, N.R.: Nanoscience in veterinary medicine. Veterinary research communications 31 (2007) 139–144.
74. Meetoo, D.D.: Nanotechnology and the food sector: From the farm to the table. Emirates journal of food and agriculture 23 (2011) 387–403.
75. Patel, G.M., Patel, G.C., Patel, R.B., Patel, J.K. Patel, M.: Nanorobot: a versatile tool in nanomedicine. Journal of drug targeting 14 (2006) 63–67.
76. Nelson, B.J., Kaliakatsos, I.K. Abbott, J.J.: Microrobots for minimally invasive medicine. Annual review of biomedical engineering 12 (2010) 55–85.
77. Barry-Ryan, C.: Physical and chemical methods for food preservation using natural antimicrobials. Handbook of natural antimicrobials for food safety and quality, Elsevier B.V, 2014.
78. Dvorak, G.: Disinfection 101. Center for food security and public health, Iowa State University, Ames, IA, 2005, pp. 1–22.
79. Rahal, A., Kumar, A., Singh, V., Yadav, B., Tiwari, R., Chakraborty, S. Dhama, K.: Oxidative stress, prooxidants and antioxidants: the interplay. Biomed research international 2014 (2014) 761264.
80. Chen, P.X., Tang, Y., Zhang, B., Liu, R., Marone, M.F., Li, X. Tsao, R.: 5-Hydroxymethyl-2-furfural and derivatives formed during acid hydrolysis of conjugated and bound phenolics in plant foods and the effects on phenolic content and antioxidant capacity. Journal of agricultural and food chemistry 62 (2014) 4754–4761.
81. Liu, Q., Wu, C., Cai, H., Hu, N., Zhou, J. Wang, P.: Cell-based biosensors and their application in biomedicine. Chemical reviews 114 (2014) 6423–6461.
82. Vashist, S.K., Venkatesh, A.G., Mitsakakis, K., Czilwik, G., Roth, G., von Stetten, F. Zengerle, R.; Nanotechnology-based biosensors and diagnostics: technology push versus industrial/healthcare requirements. Bionanoscience 2 (2012) 115–126.
83. Velasco-Garcia, M.N. Mottram, T.: Biosensor technology addressing agricultural problems. Biosystems engineering 84 (2003) 1–12.
84. Sharma, H. Mutharasan, R.: Review of biosensors for foodborne pathogens and toxins. Sensors and actuators B: Chemical 183 (2013) 535–549.
85. Rhim, J.W.: From micro to nano: a background to nanotechnology in food packaging. Progress in nanomaterials for food packaging 7 (2014) 6–18.
86. Jiang, X., Valdeperez, D., Nazarenus, M., Wang, Z., Stellacci, F., Parak, W.J. Del Pino, P.: Future perspectives towards the use of nanomaterials for smart food packaging and quality control. Particle and particle systems characterization 32 (2015) 408–416.
87. Bradley, E.L., Castle, L. Chaudhry, Q.: Applications of nanomaterials in food packaging with a consideration of opportunities for developing countries. Trends in food science and technology, 22 (2011) 604–610.

88. Duncan, T.V.: Applications of nanotechnology in food packaging and food safety: barrier materials, antimicrobials and sensors. Journal of colloid and interface science 363 (2011) 1–24.
89. Ghanbarzadeh, B., Oleyaei, S.A. Almasi, H.: Nanostructured materials utilized in biopolymer-based plastics for food packaging applications. Critical reviews in food science and nutrition 55 (2015) 1699–1723.
90. Ravindranath, S.P., Wang, Y. Irudayaraj, J.: SERS driven cross-platform based multiplex pathogen detection. Sensors and actuators B: Chemical 152 (2011) 183–190.
91. Li, Z. Sheng, C.: Nanosensors for food safety. Journal of nanoscience and nanotechnology 14 (2014) 905–912.
92. Ayala-Zavala, J.F., Gonzalez-Aguilar, G.A., Ansorena, M.R., Alvarez-Parrilla, E. de la Rosa, L.: Nanotechnology tools to achieve food safety, in practical food safety: contemporary issues and future directions (eds R. Bhat and V. M. Gomez-Lopez), John Wiley & Sons, Ltd, Chichester, UK, 2014.
93. Manzano, M., Cecchini, F., Fontanot, M., Iacumin, L., Comi, G. Melpignano, P.: OLED-based DNA biochip for Campylobacter spp. detection in poultry meat samples. Biosensors and bioelectronics 66 (2015) 271–276.
94. Sharma, T.K., Ramanathan, R., Rakwal, R., Agrawal, G.K. Bansal, V.: Moving forward in plant food safety and security through nanobiosensors: adopt or adapt biomedical technologies. Proteomics 15 (2015) 1680–1692.
95. Vanderroost, M., Ragaert, P., Devlieghere, F. De Meulenaer, B.: Intelligent food packaging: The next generation. Trends in food science and technology 39 (2014) 47–62.
96. Zou, Z., Chen, Q., Uysal, I. Zheng, L.: Radio frequency identification enabled wireless sensing for intelligent food logistics. Philosophical transactions of the royal society of London A: Mathematical, physical and engineering sciences, 372 (2014) 20130313.
97. Lopez-Gomez, A., Cerdan-Cartagena, F., Suardiaz-Muro, J., Boluda-Aguilar, M., Hernandez-Hernandez, M.E., Lopez-Serrano, M.A. Lopez-Coronado, J.: Radiofrequency identification and surface acoustic wave technologies for developing the food intelligent packaging concept. Food engineering reviews 7 (2015) 11–32.
98. Canellas, E., Vera, P. Nerin, C.: Risk assessment derived from migrants identified in several adhesives commonly used in food contact materials. Food and chemical toxicology 75 (2015) 79–87.
99. Sorrentino, A., Gorrasi, G. Vittoria, V.: Potential perspectives of bio-nanocomposites for food packaging applications. Trends in food science and technology 18 (20077) 84–95.
100. Rhim, J.W., Park, H.M. Ha, C.S.: Bio-nanocomposites for food packaging applications. Progress in polymer science 38 (2013) 1629–1652.
101. Siegrist, M., Nowack, B. Kastenholz, H.: Environmental considerations of and societal reactions to nonotechnology in the food sector (ch.12). In "Nanotechnology in the agri-food sector: implications for the future." Frewer LJ, Norde W, Fischer A. eds. John Wiley & Sons. Germany, 2011, pp. 209-223.

102. Roosen, J., Bieberstein, A., Blanchemanche, S., Goddard, E., Marette, S. Vandermoere, F.: Trust and willingness to pay for nanotechnology food. Food policy 52 (2015) 75–83.

103. Xie, Y. (Ed.). The nanobiotechnology handbook. CRC Press. Taylor and Francis Group, LLC, 2012.

104. Takeuchi, M.T., Kojima, M. Luetzow, M.: State of the art on the initiatives and activities relevant to risk assessment and risk management of nanotechnologies in the food and agriculture sectors. Food research international 64 (2014) 976–981.

105. Huang, J.Y., Li, X. Zhou, W.: Safety assessment of nanocomposite for food packaging application. Trends in food science and technology 45 (2015) 187–199.

106. Thompson, P.B: Risks and ethics in the context of food nanotechnology and the delivery of bioactive ingredients, in nanotechnology and functional foods: effective delivery of bioactive ingredients (eds Sabliov CM, Chen H, Yada RY), John Wiley & Sons, Ltd, Chichester, UK, 2015.