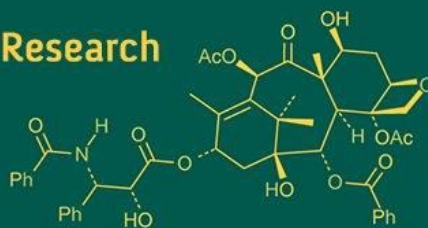


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Nanoencapsulation of vegetable phytonutrients: Health Implications, delivery techniques, and future prospects

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Abstract

Phytonutrients are the plant derived bioactive compounds associated with positive health effects. Phytochemicals is another name for them. They may offer medical health benefits, such as the prevention and treatment of disease and other physiological abnormalities, and they have a significant impact on the health care system. By preserving and adjusting immune function, phytonutrients can avoid certain diseases. Since they are natural products, they have a lot of potential for use in clinical therapy because they don't have any of the negative consequences of radiation or chemotherapy. Acts as an antioxidant and possesses anti-inflammatory activities, helps to repair DNA damage and protects from cardiovascular diseases. They can be found in vegetables, fruits, whole grains, tea, nuts, beans, spices. Including classes such as carotenoids, flavonoids, isothiocyanates, and much more.

The improper diet and unbalanced nutrition are the major reasons of malnutrition of about 3 billion people in our world which can be improved through proper balanced diet, the rest population mainly consumes only single source of nutrition such as meat, carbohydrates and proteins this is due to lack of awareness about the nutritional value of phytonutrients which can help in improving health and lifestyle of humans. There is also less progress in the field of extracting phytonutrients from vegetables and utilising them as a superfood. This void is filled via nanoencapsulation.

Nanoencapsulation is the process of enclosing a substance with in an inert material at the sizes of nano scale. The process of encapsulating phytonutrients can be done by these techniques' emulsification, coacervation, nano-precipitation, supercritical antisolvent precipitation, spray drying, freeze drying. Some of the Phytonutrients are currently being encapsulated such as β -Carotene, capsaicin, curcumin, lutein etc. Some of these products are commercially available in market with different names like CQ max, Paindex, Nutriherbs, Nano quercetin, Nano cumin, Nano ginger.

Keywords: Phytonutrients, nanoencapsulation, flavonoids, human nutrition

1. Introduction

Science, engineering, and technology carried out at the nanoscale roughly 1 to 100 nanometers is known as nanotechnology. Richard Feynman, a physicist and 1965 Nobel winner, is considered the father of nanotechnology. Norio Taniguchi of Tokyo Science University first used the word "nanotechnology" in 1974. The development of the fundamental ideas of nanotechnology took place over a longer period of time, despite the technology itself being a comparatively recent breakthrough in scientific study. The combination of experimental developments, including the development of the scanning tunnelling microscope in 1981 and the discovery of fullerenes in 1985, led to the rise of nanotechnology in the 1980s. Due to its numerous uses in a variety of fields, including health, pharmaceuticals, materials, energy, and catalysis, nanotechnology has attracted a lot of interest recently. These nanoparticles, which range in size from 1 to 100 nm, have a variety of possible uses. Both industrialised and developing nations are eager to spend more in nanotechnology since it has brought about a new economic revolution (Qureshi *et al.*, 2012) [14]. As a result, nanotechnology presents several chances for the creation and use of systems, materials, or structures with novel characteristics in a variety of fields, including food, medicine, and agriculture.

Researchers are being driven to investigate ways to improve food quality without minimising the product's nutritional content due to growing customer concerns about food quality and health advantages. The food sector has seen a rise in demand for materials based on nanoparticles since many of them are non-toxic and include vital ingredients (Roselli *et al.*, 2003) [16]. Additionally, it has been discovered that they remain stable at high pressure and temperature. From food production and processing to packaging, nanotechnology provides comprehensive food solutions. With the promise of better flavour, texture, and consistency, nanostructured food ingredients are being produced (Cientifica Report, 2006) [2]. Nanotechnology helps reduce the amount of food waste caused by microbial infestation and extends the shelf life of various food items. These days, food additives are transported in food items using nanocarriers as delivery mechanisms without changing their fundamental shape. It has been observed that in some cell lines, only submicron nanoparticles can be successfully absorbed, whereas bigger size micro-particles cannot (Ezhilarasi *et al.*, 2013) [6]. This suggests that particle size may have a direct impact on the distribution of any bioactive molecule to different places inside the body. In addition to masking smells or tastes, nanoencapsulations regulate how active ingredients interact with the food matrix, regulate the release of the active agents, guarantee availability at a predetermined time and rate, and shield them from moisture, heat, chemical, or biological deterioration during processing, storage, and use. They also show compatibility with other compounds in the system. Furthermore, because of their tiny size, these delivery methods can effectively distribute active substances to specific locations throughout the body by penetrating deeper into tissues. Many industries, including agriculture and the food sector, have hailed nanotechnology as the next big thing. From production to processing, storage, and the creation of novel materials, goods, and uses, it has been transforming the whole food system. Numerous reviews have looked at nanoencapsulation techniques in food systems, but there isn't yet a comprehensive synthesis that focusses mainly on phytonutrients, their stability problems, encapsulation effectiveness, increased bioavailability, and food-grade safety concerns. Therefore, this study critically evaluates recent developments in phytonutrient nanoencapsulation techniques, contrasts various methods, draws attention to safety and regulatory issues, and suggests future directions for functional food applications research.

2. Phytonutrients

Phyto - Greek word for plant

Nutrient - A substance that is needed to keep a living thing alive and to help it grow.

Definition: Nutrients that protect the plant from harmful oxidation, viruses, bacteria, parasites and insects are called as phytonutrients. These are the plant-derived bioactive

compounds associated with positive health effects. They are also known as phytochemicals.

Phytonutrients come in many forms:

- Natural pigments that give colors- For example in Tomato, Lycopene is the pigment that is responsible for its characteristic deep-red color and in Turmeric, Curcumin is responsible for its bright yellow color.
- Some phytonutrients are responsible for strong odors and flavors- For example, in Onion, Allyl propyl disulfide is responsible for its strong flavour.

Vitamins and minerals are the essential nutrients that our body needs to work properly, but unlike vitamins & minerals, phytonutrients are not essential to life but boost overall health and prevent chronic diseases.

2.1 Types of phytonutrients

2.1.1 Polyphenols

It includes antho- and beta-cyanins, flavonoids, isoflavones, lignans, and lignins. Blue, blue-red and violet colorations seen in berries, grapes and purple eggplant are due to their phenolic content. Blueberries, for example, are high in phenolic anthocyanidins giving them their reddish hue.

2.1.2 Alkaloids

Phytochemicals in this group are small to large complex carbon compounds which include esters and lactones. It acts as an antioxidant, cancer preventives, liver protectors, and inflammatory mediators.

2.1.3 Organosulfur group

It includes majorly glucosinolates, indoles, isothiocyanates and Allylic Sulfur Compounds. It provides the source of sulfur vital for phase-2 enzymes activity in cancer protection. Cruciferous vegetables were the first to be promoted by the American cancer society as cancer preventive.

2.1.4 Terpenoids

These are the group of unsaturated hydrocarbons, found in essential oils and oleoresins of plants used in organic syntheses. Terpenoids are classified into carotenoids and non-carotenoids. Carotenoids include lycopene, xanthophylls (lutein and zeaxanthin), alpha and beta-carotene while non-carotenoids include phytosterols, terpenes, saponin, limonene, chlorophyll.

2.2 General functions of phytonutrients

- It acts as an antioxidant and possesses anti-inflammatory activities
- Enhances overall immunity
- Repair DNA damage
- Protects from cardiovascular diseases
- Fight against cancer cells
- Detoxify the body
- Strengthen the liver
- Reduce premature aging

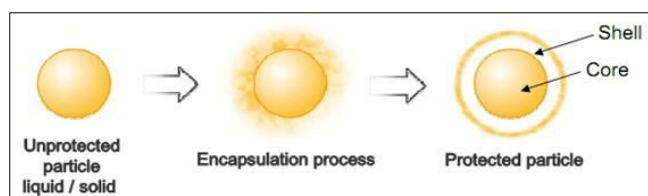
Table 1: Sources of phytonutrients from vegetables, their color and potential benefits

Colour	Phytonutrients	Potential Benefits	Found in
Purple/Blue/Red	Anthocyanins, Phenols, Resveratrol, Tannins	Antioxidants (against heart disease and stroke)	Brinjal, Beetroots, Red cabbage
Red	Lycopene	Cancer fighting antioxidant	Tomato, Watermelon, chilli.
Orange	Beta-carotene	Boosts eye and skin health	Carrots, Pumpkin, Sweet potato, Winter squash
Yellow/Green	Lutein and Zeaxanthin	Fight cataracts macular degeneration, Boosts immune system	Bell peppers, green peas, green beans, Spinach, Lettuce, Cucumber
Green	Chlorophyll, Isothiocyanate	Production of cancer-fighting liver enzymes	Broccoli, Brussels sprouts, Cabbage, Spinach
White	Allicin, Quercetin, Glucosinolates	Tumor fighting, protects cell damage, support arteries, bones and circulation	Onion, Garlic, Cauliflower

(Dias, 2012) ^[3]

3. Encapsulation

It is a process of enclosing the substances within an inert material (i.e., the material which doesn't undergoes any physical, chemical or biological transformations and it doesn't affects the other matter with which it comes into contact) which protects it from adverse environment as well as controls the release of bioactive compounds.

**Fig 1:** Encapsulation Process

3.1 There are two types of encapsulations

- 1) **Nanoencapsulation:** It is the coating of various substances within another material at sizes of nano scale. It's a process by which small particles of core materials are packed within a wall material to form capsule.
- 2) **Microencapsulation:** It is similar to nanoencapsulation aside from it involving larger particles and having been done for a greater period of time than nanoencapsulation.

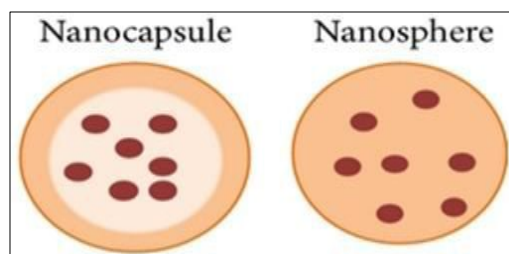
3.2 Purpose of encapsulation

- Due to the evaporation of volatile compounds or the breakdown of certain food components under the effect of air or light, a variety of foods lose their original desired flavour, taste, fragrance, and colour during processing. Volatile and unstable goods are shielded by encapsulation to prevent such impacts.
- New functional food can be created by supplementing the foodstuff with encapsulated fragrances, colorants and other components.
- Protects the encapsulated material, by providing barriers between sensitive bioactive compounds and the adverse environment (like pH, temp.).
- Controlled release of bioactive compounds
- Preserves the stability of the bioactive compounds by immobilizing them, to prevent the undesirable interactions with other food matrix or components and prevents the degradation (oxidation, hydrolysis) of bioactive compounds.
- Enhances the acceptability and bioavailability of active components.

4. Nanoencapsulation

Definition: Nanoencapsulation is defined as a technology to encapsulate substances in miniature and refers to bioactive packing at the nanoscale range (Lopez *et al.*, 2006) ^[10].

- This technique is based on enclosing a bioactive compound (BAC) within a matrix or inert material for preserving the coated substance (food or flavor molecules/ingredients). The suitable size of nano capsule is about 10-1000 nm, for the encapsulation of phytonutrients.
- Nano capsules of size, less than 10 nm are subjected to clearance by kidney excretion. Conventionally when we talk about nanomaterials, they only fall into the range of 1-100 nm, but its only in the food application, that this definition has been extended to 1000 nm.
- Polymeric nanoparticles are categories into nano capsules and nanospheres. Nano capsules are vesicular systems in which bioactive compound is confined to a cavity surrounded by a polymer membrane. Whereas nanospheres are matrix systems in which the bioactive compound is physically and uniformly dispersed.

(Orive *et al.*, 2009) ^[13]**Fig 2:** Polymeric nanoparticles

4.1 Phytonutrient encapsulation

Purpose of phytonutrients nanoencapsulation

- The demand of the functional food is increasing day by day, functional food means the food which is fortified with health-promoting additives, like phytonutrients and vitamins. Thus, phytonutrient nanoencapsulation is needed to create new functional food.
- With the help of nanoencapsulation of phytonutrients, it becomes possible to increase its gastro-intestinal retention time of bioactive compounds.
- It prevents the thermal and photodegradation of phytonutrients, during the processing and storage of foodstuff.
- Nanoencapsulation increases the bioavailability of the phytonutrients, as nanocarriers allows them to enter the bloodstream more easily from the gut.

- Phytonutrients have poor body absorption in their original form, thus nanoencapsulation increases the reactivity and bioavailability of phytonutrients.

4.2 Shell and core materials in nanoencapsulation

The material that is being encapsulated is known as core material, while the encapsulating material is known as shell material. The various shell and core materials used in the preparation of nano capsules are:

4.2.1 Shell material

- Natural polymers:** Eg. Polysaccharides - alginate, Protein -gelatin
- Synthetic polymers:** Eg. Polyamides, Melamine formaldehyde
- Lipids:** Eg. Phospholipids
- Inorganic materials:** Eg. SiO₂

4.2.2 Core material

- Aqueous Solutions
- Hydrophobic liquids
- Solids
- Gases

4.3 Specifications of shell material

- It should be a Food grade material i.e., the material made up of substances which are safe and suitable for their intended use, and which shall not change in composition and transfer harmful substances into the ingredient it is holding.
- It should provide the maximal protection against adverse environmental conditions like pH, temp., etc.
- It should not have to react with encapsulated material.
- It should be easy to work and handle during encapsulation process.

5. Techniques of nanoencapsulation

The major nanoencapsulation techniques are summarized in table 3. Emulsification, coacervation, inclusion complexation, emulsification-solvent evaporation, nanoprecipitation and supercritical fluid technique are considered as nanoencapsulation techniques since they can produce capsules in the nanometer range (10-1,000 nm). Both top-down and bottom-up methods are used in

nanoencapsulation procedures to create nanomaterials Table 2. Using precise techniques that enable size reduction and structural sculpting for the intended use of the nanomaterials being created is part of a top-down strategy. According to Augustin and Sanguansri (2009), the bottom-up technique builds materials by the self-assembly and self-organization of molecules, which are impacted by a variety of variables such as pH, temperature, and ionic strength.

The top-down technique makes use of methods like emulsification and emulsification-solvent evaporation. Conversely, the bottom-up strategy makes use of inclusion complexation, coacervation, supercritical fluid technology, and nanoprecipitation. Numerous hydrophilic and lipophilic bioactive substances can be encapsulated using these nanoencapsulation processes. Both hydrophilic and lipophilic molecules are encapsulated via emulsification, coacervation, and supercritical fluid techniques (Leong *et al.*, 2009) [9]. However, lipophilic chemicals are primarily treated via inclusion complexation, emulsification-solvent evaporation, and nanoprecipitation methods (Reis *et al.*, 2006) [15].

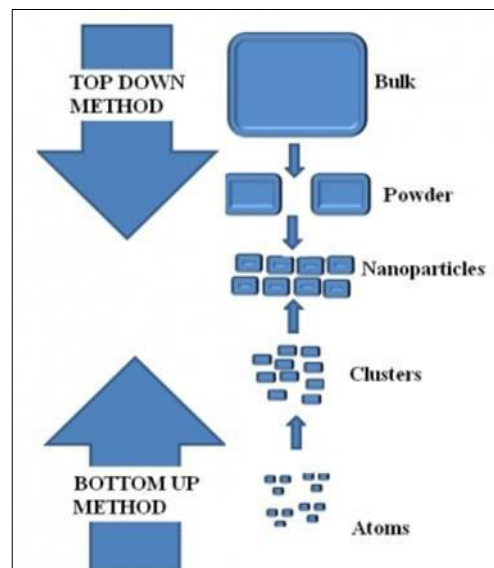


Fig 3: Top-down and bottom-up approaches in nanoencapsulation techniques

Table 2: Top-down and bottom-up approaches in nanoencapsulation techniques

Approach	Principle	Technique involved	Characteristic	Food application suitability
Top down	Size reduction using mechanical energy	Emulsification, high pressure homogenization	High energy input, scalable	Widely used
Bottom up	Self-assembly of molecules	Nanoprecipitation, coacervation, supercritical fluids	Controlled particle formation	Selective, high precision

Table 3: Nanoencapsulation techniques used for phytonutrients

Technique	Suitable compounds	Particle size (nm)	Suitable bioactive compounds	Raw materials used	Advantages	Limitation
Emulsification	Formation of nano emulsions using high-energy or low-energy input	50-1000	Lipophilic and hydrophilic	Wall materials: Chitosan Emulsifier: Tween-20	High kinetic stability, easy scaleup, food compatible	Requires high energy, droplet coalescence if unstable
Coacervation	Phase separation of oppositely charged polymers	100-600	Mainly lipophilic	WM: Gelatin, maltodextrin Emulsifiers: Tween-60 Other materials:	High encapsulation efficiency, controlled release	Use of cross-linkers, sensitivity to pH and ionic strength

				Glutaraldehyde		
Nano-precipitation	Solvent displacement and polymer precipitation	<100	Lipophilic	WM: Ethyl and methyl cellulose Emulsifiers: Gelatin or Tween-20	Simple, reproducible, narrow size distribution	Limited solvent selection
Inclusion complexation	Entrapment of guest molecules into host cavities	<100	Volatile and lipophilic	Cyclodextrins	Masking odors, improved stability	Limited to small molecules
Emulsification-solvent evaporation	Polymer precipitation after solvent evaporation	100-500	Lipophilic	PLA, PLGA, ethyl cellulose	Controlled particle size, good stability	High energy demand, solvent residues
Supercritical fluid technique	Solvent extraction using supercritical CO ₂	100-300	Thermo-sensitive compounds	Wall materials: Hydroxylpropyl methyl cellulose phthalate	Minimal solvent residue, mild condition	Expensive equipment
Spray drying	Rapid solvent evaporation by hot air	300-600	Heat-stable compounds	Wall materials: Modified n-octenyl succinate starch	Economical, industrially established	Produces micro-sized particle
Freeze drying	Sublimation of frozen solvent	100-500	Heat-sensitive compounds	Wall materials: PLC and gelatin Emulsifiers: Pluronic F-68	Preserves structure and activity	High cost, porous particle

6. Problems and Safety Issues on Nanoencapsulation

Protection, regulated distribution, and improved bioavailability of bioactive compounds are made possible by the development of the nanoencapsulation method. In addition to its progress, it has brought up a variety of safety, environmental, ethical, and regulatory concerns that result from our ignorance of how nano-sized materials affect the environment and human health (EFSA 2009). The bio-transformation of nanoparticles following oral delivery was a crucial aspect of nanoencapsulation that received little attention. Less was known about even the excretion of nanoparticles (FAO 2009). Particle size, mass, chemical composition, surface characteristics, and the aggregation of individual nanoparticles all generally affect how harmful nanoparticles are to the body. According to a European Food Safety Authority report (EFSA 2009), in order to address the dangers associated with nanotechnologies, current risk assessment approaches for micro/nanoscale compounds need to be changed. The usage of nanoparticles as authorised food ingredients or additions in food or materials that come into contact with food is unclear. They should be considered unique items that need to be evaluated and approved, and the authorities in charge of regulation must make explicit declarations concerning their usage.

An internal FDA nanotechnology task group was established in 2006 to decide on regulatory strategies for nanomaterials (FDA 2006). Furthermore, precise inclusion or exclusion criteria for nano-specific risk assessment are not provided by the existing level of knowledge about the special characteristics of manufactured nanomaterials. As a result, taking into account a variety of possible characteristics, such as distinctive biological or physical behaviour and their toxicological evaluation, may be helpful in the risk assessment (FAO 2009). There will be a protracted debate over the advantages and disadvantages of using nanotechnology in the food sector. Furthermore, there is currently no solid evidence about the negative health effects of nanotechnology in the food chain. As a result, it is prudent to implement regulatory controls as a proactive way to safeguarding the public from the possible negative consequences of nanotechnology until proven otherwise. Furthermore, current scientific knowledge of nanotoxicity must be closely linked to newly developed nano goods in order to produce updated nanofood laws that minimise the potential health effects of nanotechnology (Chau *et al.*, 2007) [1].

Safety concern of nanoscale materials and nano encapsulated food nano materials may be evaluated under 3 categories -

- Nanomaterials as indirect food contaminants
- Nanoparticles which modify the digestion process as well as the absorption
- Nanoparticles with unknown toxicity

7. Commercial Products

Products	Bioactive Compound
CQ MAX	Curcumin
PAINDEX	Curcumin, Lycopene and Piperine
NUTRIHERBS	Curcumin
Nano Quercetin	Lutein

8. Future perspectives

Despite significant breakthroughs in phytonutrient nanoencapsulation techniques, numerous major research gaps must be addressed before they may be used safely, effectively, and on a broad scale in food systems. Future research should focus on developing food-grade, biodegradable, and sustainable nanocarriers produced from natural polymers such as proteins, polysaccharides, and lipids, while lowering reliance on synthetic polymers and organic solvents (McClements, 2018; Silva *et al.*, 2020) [12, 17].

The creation of smart and stimuli-responsive nanocarriers offers a viable option for future research. Such systems, which can release phytonutrients in response to pH changes, enzymatic activity, or redox conditions, have the potential to dramatically improve targeted delivery and bioavailability while reducing dosage requirements (McClement, 2018) [12]. Furthermore, combining nanoencapsulation with upcoming technologies like spray-freeze drying, electrospinning, and green supercritical fluid techniques should improve encapsulation efficiency and product stability (López-Rubio *et al.*, 2022) [11].

Future research must link technology innovation with safety evaluation and honest risk communication in order to be regulatory and consumer-friendly. Harmonisation of international laws, the creation of nano-specific risk assessment frameworks, and the generation of strong toxicological data are critical for ensuring consumer trust and regulatory approval (EFSA, 2021). Interdisciplinary collaboration among food scientists, toxicologists, regulatory agencies, and industry stakeholders will be critical for developing nanoencapsulation technologies for

safe, sustainable, and commercially successful functional food applications.

9. Conclusion

Nanoencapsulation-based technologies are unique and modern, and their application opens up new business potential. Their use is the development of nanostructured food additives that improve the solubility, stability, flavour, colour, and texture of foods during processing and storage. It has a larger potential for increasing the efficacy of bioactive ingredient delivery to benefit human health. It is a viable solution for masking undesirable flavours or odours while simultaneously increasing the bioavailability and regulated release of several nutrients in meals. The potential risks of nanoparticles on human health are unclear and must be investigated and examined. Nanotechnology's success in the food and bioprocessing industries is dependent on customer perception and societal acceptability.

References

1. Chau CF, Wu SH, Yen GC. The development of regulations for food nanotechnology. *Trends Food Sci Technol.* 2007;18(5):269-280.
2. Cientifica. Nanotechnologies in the food industry. London: Cientifica; 2006: <http://www.cientifica.com/www/details.php?id47>
3. Dias JS. Major classes of phytonutriceuticals in vegetables and health benefits: a review. *J Nutr Ther.* 2012;1(1):31-62.
4. European Food Safety Authority. Scientific opinion on the potential risks arising from nanoscience and nanotechnologies on food and feed safety. *EFSA J.* 2009;958:1-39.
5. EFSA Panel on Food Additives and Flavourings. Guidance on risk assessment of nanomaterials to be applied in the food and feed chain. *EFSA J.* 2021;19(8):e06768.
6. Ezhilarasi PN, Karthik P, Chhanwal N, Anandharamakrishnan C. Nanoencapsulation techniques for food bioactive components: a review. *Food Bioprocess Technol.* 2013;6(3):628-647.
7. Food and Drug Administration. FDA forms internal nanotechnology taskforce. Silver Spring (MD): FDA; 2006: <http://www.fda.gov/bbs/topics/NEWS/2006/NEW01426.html>
8. Food and Agriculture Organization of the United Nations. FAO/WHO expert meeting on the application of nanotechnologies in the food and agriculture sectors: potential food safety implications. Rome: FAO; 2009.
9. Leong TSH, Wooster TJ, Kentish SE, Ashokkumar M. Minimising oil droplet size using ultrasonic emulsification. *Ultrason Sonochem.* 2009;16(6):721-727.
10. Lopez A, Gavara R, Lagaron JM. Bioactive packaging: turning foods into healthier foods through biomaterials. *Trends Food Sci Technol.* 2006;17(10):567-575.
11. López-Rubio A, Gavara R, Lagaron JM. Nanostructured delivery systems for food bioactive compounds. *Curr Opin Food Sci.* 2022;43:100806.
12. McClements DJ. Nanotechnology approaches for improving bioavailability of phytochemicals. *Food Chem.* 2018;238:1-10.
13. Orive G, Anitua E, Pedraz JL, Emerich DF. Biomaterials for promoting brain protection, repair and regeneration. *Nat Rev Neurosci.* 2009;10:682-692.
14. Qureshi AM, Swaminathan K, Karthikeyan P, Ahmed KP, Sudhir, Mishra UK. Application of nanotechnology in food and dairy processing: an overview. *Pak J Food Sci.* 2012;22:23-31.
15. Reis CP, Neufeld RJ, Ribeiro AJ, Veiga F. Nanoencapsulation I: methods for preparation of drug-loaded polymeric nanoparticles. *Nanomedicine.* 2006;2:8-21.
16. Roselli M, Finamore A, Garaguso A, Britti MS, Mengheri E. Zinc oxide protects cultured enterocytes from the damage induced by *Escherichia coli*. *J Nutr.* 2003;133:4077-4082.
17. Silva HD, Cerqueira MA, Vicente AA. Nanoencapsulation of bioactive compounds for food applications: a review. *Trends Food Sci Technol.* 2020;95:138-152.