Review Article
Open Access
CrossMark

Microencapsulation of bioactive food ingredients and controlled release-a review

Abstract

Microencapsulation is a process of coat¬ing of small particles of solid or liquid material (core) with protective coating material (matrix) to produce microcapsules in the micrometer to millimeter range. It is one of the methods of protecting sensitive substances and producing active ingredients with improved properties. Many different active materials like lipids, proteins, vitamins and minerals, enzymes and flavors have been successfully encapsulated. To produce effective encapsulated products, the choice of coating material and method of microencapsulation process are most important and it also depends on the end use of the product and the processing conditions involved. These microcapsules release their contents at desired rate and time by different release mechanisms, depending on the encapsulated products which provide wide application of food ingredients thereby improving the cost effectiveness for the food manufacturer. This review paper highlighted the various microencapsulation methods and its application in the encapsulation of bioactive food ingredients and controlled release mechanisms.

Keywords: microencapsulation, microcapsules, food ingredients, bioactives, controlled release2

Volume 2 Issue 6 - 2016

Jeyakumari A, Zynudheen AA, Parvathy U
ICAR-Mumbai research of centre of Central Institute of Fisheries Technology, India

Correspondence: Jeyakumari A, ICAR-Mumbai research of centre of Central Institute of Fisheries Technology, India, Email jeya131@gmail.com

Received: May 16, 2016 | **Published:** September 07, 2016

Introduction

Now-a-days the demand for healthy and nutritional food products is increasing worldwide. Today foods are intended not only to fulfill the hunger and to provide necessary nutrients for humans. It also intended to prevent nutrition-related diseases and improve physical and mental health. In this regard, functional foods play an outstanding role. Functional foods are foods that enriched with functional ingredients to offer health benefits or to reduce the risk of chronic diseases beyond their basic nutritional functions. Bioactive in food are physiologically active components that provide health benefits beyond their nutritional role. Bioactive ingredients include proteins, vitamins, minerals, lipids, antioxidants, phytochemicals and probiotic bacteria.[1] These bioactives are very sensitive and their application in food is a great challenge to the industry without affecting their properties. Encapsulation technology has proven to be an excellent method to protect the sensitive food ingredients and to develop the novel foods formulations with improved properties.[2–3] Microencapsulation defined as a process of coating small particles of solids, liquids, or gaseous components, with protective coating material.[4] Microcapsules or micron size ranged from 2-5000µm. In the food industry, the microencapsulation process can be applied for a various purpose[5] such as

i. To protect the core material from degradation and to reduce the evaporation rate of the core material to the surrounding environment;
ii. To modify the nature of the original material for easier handling;
iii. To release the core material slowly over time at the constant rate
iv. To prevent unwanted flavor or taste of the core material;
v. To separate the components of the mixture that would react one another. Depends on the consumer needs, microencapsulation process has been improved constantly. As a result, it has become an example of a dynamic and technological intensive process method,[6] characterized by a fast growth of patent in microencapsulation process and its applications, as well as by an increasing number of scientific research articles.

There are separate extensive reviews on microencapsulation techniques used in the food industry. However, there is a need to discuss the different carriers and methods with a particular focus on encapsulating bioactive food ingredients. The objective of this paper is to review the microencapsulation technologies in a three perspectives. First, it focuses on theoretical aspects of different types of microencapsulation techniques and criteria required for encapsulating agents. Next, it discusses microencapsulation of various bioactive food ingredients such as omega-3 fatty acids, polyphenols, enzymes, protein hydrolysate and peptides, microorganisms, vitamins and minerals and its applications. The third section summarizes controlled release mechanisms of microcapsules.

Overview of microencapsulation technologies

The material that is encapsulated is called as core material, the active agent, internal phase, or payload phase. The substance or material that is encapsulating the core is called as wall material, coating material, membrane, shell, carrier material, external phase or matrix. Two main types of encapsulates are reservoir type and matrix type.[7] In reservoir type, the active agents form a core surrounded by an inert barrier. It is also called single-core or mono-core or core-shell type. In matrix type, the active agent is dispersed or dissolved in an inert polymer. Coated matrix type is a combination of first two (Figure 1).

The microcapsules are prepared by a variety of methods. The microencapsulation process can be divided into physical and chemical process. Physical process includes spray drying, spray chilling, rotary disk atomization, fluid bed coating, coextrusion and pan coating. The chemical process includes simple and complex coacervation,

interfacial polymerization and phase separation.[8,9] Different types of microencapsulation techniques and their properties, merits and demerits are summarized in Table 1.

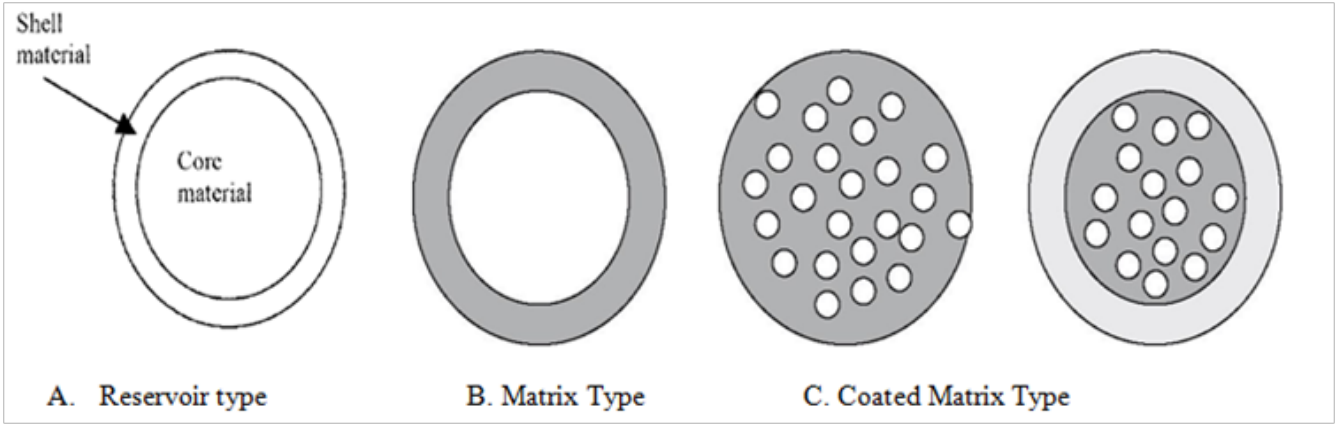

Figure 1 Morphology of microcapsule.

Table 1 Overview of advantages and Dis-advantages of microencapsulation methods5, 7–10

Methods	Major steps in process	Particle size (µm)	Morphology	Advantages	Disadvantages
Spray-drying	• Dissolve active in aqueous coating solution Homogenization of the dispersion ♦ Atomization ♦ Dehydration of the atomized particles	10 -400	Matrix	♦ Relatively simple, fast and easy to scale-up, equipment is readily available ♦ The cost of spray-drying method is 30–50 times cheaper ♦ Both hydrophilic and hydrophobic polymer can be used	♦ Considerable amounts of the material can be lost during the process due to sticking in the wall of the drying chamber ♦ Process variables that should be optimized for encapsulation
Spray cooling or Spray chilling	♦ Disperse active in heated lipid solution ♦Homogenization of the dispersion ♦ Atomization ♦ Cool	20-200	Matrix	♦ Least expensive ♦ Active compounds released within a few minutes after being incorporated in the food stuff	♦ Not a true /proper microencapsulation process

Table Continued

Methods	Major steps in process	Particle size (µm)	Morphology	Advantages	Disadvantages
Fluid bed coating	♦ Preparation of coating solution ♦ Fluidization of core particles. ♦ Coating of core particles ♦ Dehydrate or cool	May-00	Reservoir	♦ Uniform layer of shell material onto solid particles.	♦ Control of air stream and air temperature is a critical factor ♦ To achieve uniform coating droplets must be significantly smaller than core.
Spinning disk and centrifugal co-extrusion	♦ Preparation of core and coating solution ♦ Co-extrusion of core and coat solution through nozzles	150-8000	Reservoir	♦ Product outputs are comparable or even higher than regular spray drying or spray cooling processes	♦ Higher space consumption ♦ Direct observation of the particles during production is more difficult
Extrusion	♦ Preparation of molten coating solution ♦ Dispersion of core into molten polymer ♦Cooling or passing of core-coat mixture through dehydrating liquid	200-5000	Matrix	♦ Product shelf life is long (eg.5 years for extruded flavor oils)	♦ Large particles formed by extrusion ♦ Very limited range of shell material is available
Freeze-Drying / Lyophilization	♦ Mixing of core in coating solution ♦ Freeze-drying of the mixture ♦ Grinding (option)	20-5000	Matrix	♦ Product with good resistance to oxidation ♦ Maintain the shape of microcapsule	♦ High energy use, the long processing time, and the open porous structure obtained. ♦ Compared to spray-drying, freeze-drying is upto 30–50 times more expensive
Coacervation	♦ Formation of a three-immiscible chemical phases ♦ Deposition of the coating ♦ Solidification of the coating	10 - 800	Reservoir	♦ Does not include an aqueous continuous phase, this makes encapsulation water-soluble compounds	♦ Mass production is difficult due to agglomeration

Table Continued

Methods	Major steps in process	Particle size (µm)	Morphology	Advantages	Disadvantages
Supercritical fluids Technology:	♦ Create a dispersion of active agent in supercritical fluid	10 - 400	Matrix	♦ No requirements of surfactants, yielding a solvent-free product, and moderate process conditions	♦ All solutes should be soluble in the supercritical fluid.
	♦ Release the fluid to precipitate the shell on to the active			♦ The process does not include toxic organic solvents nor produce w/o interface where many proteins may be denatured	♦ Morphology of the precipitate can be difficult to control and predict
Liposome Entrapment	♦ Microfluidization	10-1000	Various	♦ Leptosomes are mainly studied and used as advanced, pharmaceutical drug carriers and their use in foods	♦ Limited due to its chemical and physical instability.
Co-crystallization	♦ Ultrasonication	Feb-30	Cluster like agglomerate	♦ Improved solubility, homogeneity, hydration and flowability	♦Low encapsulation yield
	♦ Reverse-phase evaporation				
	♦ Preparation of supersaturated sucrose solution				The granular product has a lower hygroscopicity
	♦ Adding of core into supersaturated solution			♦ Core material in a liquid form can be converted into dry powdered form without additional drying	♦ Heat sensitive core material may get degrade during process
	♦ Emission of substantial heat after solution reaches the sucrose crystallization temperature				
Inclusion complexation	♦ Preparation of complexes by mixing or grinding	15-May	Molecular inclusion	♦ Protection of unstable and high value speciality flavor chemicals	♦ Limited amount of flavor (9%-14%) can be incorporated
	♦ Incubate and dry if necessary				♦ Cyclodextrin is very expensive

Microencapsualtion bio active ingredients

There are numerous methods are used for microencapsulation of bioactive ingredients. But no single encapsulation process is applicable to all core materials or active agent. Microencapsulation methods used for various bioactive ingredients are discussed below:

Encapsulation of omega-3 fatty acids

Omega-3 fatty acids are belongs to the family of polyunsaturated fatty acids that the body cannot synthesize, but are essential for multiple function in human health. Biochemically, omega-3 fatty acids which have their first double bond (unsaturated) in the third carbon from the methyl end. The most important omega-3 fatty acids are alpha linolenic acid (ALA, 18:3 n-3), eicosapentaenoic acid (EPA, 20:5n-3) and docosahexaneoic acid (DHA, 22:6n-3). Due to its unsaturated nature, they are susceptible to oxidation and also produce hydro peroxides and off-flavours which are objectionable by consumers. To overcome the above mentioned problems, the utilization of microencapsulation technique has been studied by various researchers.[11–14] Different methods used for microencapsulation of omega-3 fatty acids are given in Table 2.

Encapsulation of polyphenols/flavors

Flavor plays an important role in food products which influences further consumption of foods and provide consumer satisfaction. The market for flavors is focused in using aromatic materials coming from natural sources to replace the use of synthetic flavors in the food products.[15] These aroma compounds are not only delicate and volatile, but also very expensive.[10] Commercially available food flavors in liquid forms are difficult to handle or incorporate into food systems. However, many flavor constituents are very sensitive to oxygen, light, and heat. These problems can be solved by encapsulation. Encapsulation provides an effective method to protect flavor compounds from degradation, oxidation and migration from food. Essential oils (Eos) are volatile, complex mixtures of compounds characterized by a strong odor, and they are formed by aromatic plants as secondary metabolites. Several essential oils such as ginger, garlic, cinnamon, coriander, clove, peppermint, citrus peel, oregano, thyme, rosemary basil, eucalyptus and have been demonstrated various biological properties activities, including antioxidant, antimicrobial, antiviral and anti-inflammatory functions.[16,17] Several researchers reported that plant polyphenols can slow the progression of cancers, diabetes, and osteoporosis and reduce the risks of cardiovascular disease.[18,19] Due their instability and unpleasant taste (astringency) which needs to be protected or masked before incorporation into food products.[20] Different methods used for encapsulation of polyphenols are given in Table 3.

Encapsulation of vitamins and minerals

Fat-soluble (e.g. A, D, E, K) and water-soluble (e.g. ascorbic acid) vitamins can be encapsulated by microencapsulation.[23] Iron is one of the most important elements and plays a major role in human health and its inadequate consumption leads to iron deficiency. One of the ways to prevent this problem is fortification of food with iron. But, the bioavailability of iron is affected by interactions of iron with the food ingredients such as tannins, phytates and polyphenols. Moreover, iron catalyses oxidative processes in fatty acids, vitamins and amino acids, which results in loss of sensory features and decrease in nutritional value of the food. Microencapsulation can be used to prevent these reactions. Microencapsulation methods used for vitamins and minerals are given in Table 4.

Encapsulation of calcium

Soya milk contains much less calcium (12mg/100g) than cow's milk (120mg/100g), which is undesirable from a nutritional point of view. By encapsulating the Ca salt (calcium lactate) in a lecithin liposome, provides possible to fortify 100g soya milk with calcium up to 110mg for obtaining calcium levels equivalent to those in normal cow's milk.[26]

Encapsulation of enzymes

Enzymes are biomacromolecules or in other words complex protein molecules with specific catalytic functions and they regulate the chemical reactions needed for the human body. Because of their enormous catalytic power in aqueous solution at normal temperatures and pressures, enzymes are of great commercial and industrial importance. In the microencapsulation method, the enzyme is entrapped within a semi permeable membrane so that the activity of an enzyme is not affected (Table 5). But the movement of the substrate to the active site may be restricted by the diffusional limitations especially when large molecules like starch and proteins are used, which can have an adverse effect on the enzyme kinetics.[27]

Encapsulation of microorganism

Probiotic bacteria are the live microorganisms that are confer a beneficial physiological effect on the host (humans or animals). These bioactive ingredients have been at the forefront of the development of functional foods, particularly in dairy products.[30] There are five microencapsulation methods have been applied to probiotics such as spray-coating (fluid bed coating), spray-drying, extrusion, emulsion and gel particle technologies (which include spray-chilling). Among these spray-coating and gel-particle technologies are most often used for microencapsulation of probiotics.[31] Different wall materials used for microencapsulation of microorganisms are given in Table 6.

Encapsulation of protein hydrolysate and peptide

Food protein hydrolysates and peptides are considered as a promising functional food ingredients. However, food application of protein hydrolysates and peptides can be inhibited by their bitter taste, hygroscopicity and interaction with the food matrix. These problems can be solved by encapsulation.[33] Proteins, polysaccharides and lipids based carrier systems used for protein hydrolysates and peptide encapsulation (Table 7). The protein and polysaccharide based carried used for masking the bitter taste and reducing the hygroscopicity of protein hydrolysates, whereas the lipid-based carriers are intended for enhancing the bioavailability and biostability of encapsulated peptides.

Application of microencapsulated bioactive ingredients in food industry

Microencapsulation offers numerous benefits to the materials being encapsulated. Some of the encapsulated food ingredients and their applications are summarized in Table 8.

Citation: Jeyakumari A, Zynudheen AA, Parvathy U. Microencapsulation of bioactive food ingredients and controlled release-a review. *MOJ Food Process Technol.* 2016;2(6):214–224. DOI: 10.15406/mojfpt.2016.02.00059

Table 2 Methods and wall material used for microencapsulation of omega-3 fatty acids.[14]

Methods	Wall Material
Spray drying (fish oil)	Gelatin, maltodextrin, casein, lactose, sodium caseinate, dextrose equivalence, highly branched cyclic dextrin, methylcellulose, hydroxypropyl methylcellulose, n-octenylsuccinate, derivatized starch/glucose syrup or trehalose, sugar beet pectin, gum arabic, corn syrup solids, egg white powder
Spray drying (flaxseed oil)	Whey protein isolate, gum arabic and lecithin, maltodextrin, whey protein concentrate, gum arabic and two chemically modified starches, tapioca starch and waxy maize,
Freeze-drying (fish oil)	sodium caseinate, carbohydrate, egg white powder, gum arabic, lactose and maltodextrin
Freeze-drying (flaxseed oil)	Gelatin
Simple coacervation	Hydroxypropyl methylcellulose
Complex coacervation	Gelatin-gum arabic with transglutaminase (TG) as cross-linking agent
Electrostatic layer by layer (multilayer) deposition and Spray drying (fish oil)	Lecithin and chitosan
Double emulsification and subsequent enzymatic gelation (fish oil)	Soy protein, whey protein, wheat protein sodium caseinate, transglutaminase
Ultrasonic atomization and freeze drying (fish oil)	Chitosan
Electrospraying (fish oil)	Zein prolamine (corn protein)
Spray granulation and fluid bed film coating (fish oil)	Soybean soluble polysaccharide (SSPS) and maltodextrin, hydroxypropyl beta cyclodextrin (HPBCD)

Table 3 Methods, wall material used for encapsulation of polyphenols[21–22]

Methods	Wall material	Polyphenols
Spray Drying	Maltodextrin, gum arabic, chitosan, citrus fruit fiber, colloidal silicon dioxide, Maltodextrin and starch, sodium caseinate-soy lecithin, skimmed milk powder, whey protein concentrate, gelatin	Black carrot extracts (anthocyanins), procyanidins, olive leaf extract, *Hibiscus sabdariffa* L. extract (anthocyanins), soybean extract, grape seed extract, apple polyphenol extract and olive leaf extract, oregano essential oil, mint oil, cardamom oleoresin, black pepper oleo resin , cumin oleo resin, turmeric oleo resin
Coacervation	Calcium alginate , chitosan, gelatin (type A), glucan, chitosan and κ-carrageenan	Yerba mate extract, EGCG, black currant extract, Pimento oil
Cocrystallization	Sucrose syrup	Orange peel oil
Freeze drying	Maltodextrin DE20, maltodextrins DE 5-8 and DE18.5, pullulan	Anthocyanin, cloudberry extract, Hibiscus anthocyanin, orange oil,
Molecular encapsulation	HP-β–CD, β-CD and maltosyl- β–CDs, α-CDs, hydrophobically modified starch	3-hydroxyflavone, morin and quercetin, , ferulic acid, rutin, curcumin, citrus oils, cinnamon leaf and garlic oil, citrus oil
Extrusion	Corn syrup solids, glycerine, sodium alginate	Citrus oil, clove oil, thyme oil, cinnamon oil
Electrostatic extrusion	Calicium alginate gels	Ethyl vanilline (3-ethoxy-4- hydroxybenzaldehyde)

Table 4 Methods and wall material used for microencapsulation of vitamins and minerals[23–25]

Method	Wall Material	Active Agents
Spray drying	Tripolyphosphate, cross-linked chitosan, starch, β-cyclodextrin, malto dextrin, gum arabic,	Vitamin C, vitamin A
Spray cooling and spray chilling	Waxes, fatty acids, water-soluble polymers and water-insoluble monomers, soy lecithin	Ferrous sulphate, vitamins, minerals, acidulants.
Liposome entrapment	Egg phosphatidylcholine, cholesterol, DL-α-tocopherol	Vitamin C, Iron
Extrusion	Maltodextrin (DE 7-10), lactose, fructo-oligosaccharide	Vitamin C
Fluidised bed coating	Polymethacrylate, ethylcellulose, waxes, hydrogenated vegetable oil, stearin, fatty acids, emulsifiers, gums and maltodextrins	Vitamin C
Coacervation	Gelatin and acacia	Vitamin A
Molecular inclusion	β-cyclodextrin, Maltodextrin	Vitamin A
Liposome entrapment	Hormones, enzymes and vitamins	Liposome entrapment

Table 5 Methods and wall material used for microencapsulation of enzymes[27–29]

Method	Wall material	Enzymes
Liposome	Alginate	Proteolytic enzyme
Complex coacervation	Chitosan/Cacl2 polyelectrolyte beads, Sodium alginate and starch	Protease enzyme, Flavourzyme®
Spray drying	Chitosan, modified chitosan (water soluble), alginate, calcium alginate and arabic gum, α-amalase,	β-Galactosidase, lipase from Y. lipolytica
Liposome entrapment	Alginate, carrageenan	Mixture of proteolytic and lipolytic enzyme

Table 6 Wall materials used for microencapsulation of microorganisms.[32]

Wall material	Microorganisms
Alginate and its combinations	Lactic acid- and probiotic bacteria
High-amylose corn starch,	Probiotic bacteria
Mixture of xanthan-gelan	Probiotic bacteria
Carrageenan and its mixtures	Lactic acid bacteria such as *Streptococcus salivariuss sp. Thermophiles and Lactobacillus delbrueckiis sp. Bulgaricus* (traditional yogurt bacteria), *Bifidobacterium sp.*
Gelatin or gelatin and gum	Lactobacillus lactis
Cellulose acetate phethalate	Bifidobacterium pseudolangum
Mixture of chitosan and hexamethylene di isocyanate	Probiotic bacteria

Table 7 Methods and wall material used for microencapsulation of protein hydrolysate and peptide

Method	Wall material	Hydrolysates and peptide
Spray drying	Soy protein isolate, gelatin, whey protein concentrate, alginate, maltodextrin, gum Arabic, carboxymethylated gum	Casein hydrolysate, whey protein hydrolysate, rapeseed peptide, chicken hydrolysate,
Coacervation	Soy protein isolate and pectin	Casein hydrolysate
Liposome entrapment	Phosphatidyl choline, phosphatidyl glycine, lecithin, stearic acid and cupuacu butter	Fish hydrolysate, sea bream collagen peptide fraction, casein hydrolysate

Table 8 Application of microencapsulated bioactive ingredients in food industry5

Type of encapsulated food ingredients: examples	Purpose
Lipids: Fish oil, linolenic acid, rice bran oil, sardine oil, palmitic acid, seal blubber oil	To prevent oxidative degradation during processing and storage
Flavoring agents: Citrus oil, mint oils, onion oils, garlic oils, spice oleoresins	To transform liquid flavorings into stable and free flowing powders which are easier to handle
Vitamins : Fat soluble: vitamin A, D, E and K. Water soluble : Vitamin C, vitamin B_1, vitamin B_2, vitamin B_6, vitamin B_{12}, niacin, folic acid	Reduce off-flavors, permit time-release of nutrients, enhance the stability to extremes in temperature and moisture, reduce each nutrient interaction other ingredients
Enzymes and microorganisms: Lipase, invertase, *Brevebacterium linens*, *Penicillium roqueforti*, *Lactic acid bacteria*	Improve stability during storage in dried form, reduces the ripening time; Improve the stability of starter cultures; Improved retention in finished products

Type of encapsulated food ingredients: examples	Purpose
Acidulants: Lactic acid, glucono-g-lactone, Vitamin C, acetic acid, potassium sorbate, sorbic acid, calcium propionate, and sodium chloride	Used to assist in the development of color and flavor. Baking industry uses stable acids and baking soda in wet and dry mixes to control the release of carbon dioxide during processing and subsequent baking.
Sweetners: Sugars, nutritive or artificial sugars; aspartame	To reduce the hygroscopicity, improve flowability, and prolong sweetness perception
Colorants: Annato, β-carotene, turmeric	Encapsulated colours are easier to handle and offer improved solubility, stability to oxidation, and control over stratification from dry blends

Controlled release mechanism

Controlled release has been defined as a method by which one or more active agents are occurs at the target site and at the desirable rate and time.[36] The major objectives of controlled release are to decrease the loss of target compound such as vitamins and minerals during the processing and storage, to optimize the absorption and to increase of effective use. The advantages of controlled release are; the active ingredients are released at controlled rates over prolonged periods of time.[37] The most commonly used methods for controlled release includes thermal and moisture release.[38] The major mechanisms involved in the core release are pH, temperature, use of solvent, diffusion, degradation and swelling or osmotic pressure activated release. Normally, a combination of more than one mechanism is used for release of core material.[5]

Diffusion-controlled release

In this method, core or active material is released by diffusion through the polymer (reservoir system) or through the pores existing in the polymer (matrix systems).

Reservoir systems: The release of an active agent by this method is carried out by diffusion of the active agent within the reservoir; dissolution of the active agent between the reservoir carrier fluid and the barrier. The release rate from a reservoir system depends on the permeability, area and thickness of the barrier.[39]

Matrix systems: The active agent is released by this method is carried out by diffusion of the core material to the surface of the coating material; dissolution of the active agent between the carrier and the surrounding medium. The rate release depends on the percentage of active agent, coating material and the geometry of the system.[39]

Swelling controlled release: In this method, when the polymer matrix is placed in a thermodynamically compatible medium, the polymer swells which leads to absorption of fluid from the medium. The active agent in the swollen part of the matrix then diffuses out.[40]

Release of active agent by degradation: Degradation type of release occurs when enzymes such as proteases and lipases are degraded in to proteins or lipids, respectively.[41] An example of release of active agent by degradation is reducing the time required for the ripening of cheddar cheese by 50% compared to conventional ripening process.[42]

Solvent-activatedrelease: The active agent is released when the food material comes in contact with a solvent, resulting in swelling of the microcapsule. For example, microencapsulated of coffee flavors is released upon contact with water.[43]

pH-controlled release: The active agent is released at a specific pH. For example, microencapsulated probiotic microorganisms will resist in the acidic pH of the stomach and it will be released in the alkaline pH of the intestine.[44]

Temperature-sensitive release: The active agent is released according to the change of temperature. Examples are, aromas for tea and baking are based on the effect of melting of the matrix; encapsulated cheese flavor used in microwave popcorn release the flavor when the temperature rises to 57-90˚C.[45]

Pressure-activated release: In this method, the active agent is released when the pressure is applied on the matrix. For example, release of sweetener and/or flavor in chewing gum when chewed.[46]

Conclusion

Microencapsulation process provides an effective protection for active agent against oxidation, evaporation or migration in food. It plays a major role in development high quality functional food ingredients with improved physical and functional properties in order to make superior products. To produce effective encapsulated products, the choice of coating material and method of microencapsulation process are most important. Despite the wide range of application of encapsulated products in pharmaceutical and cosmetic industries, microencapsulated product has found a comparatively much smaller market in the food industry. The microencapsulation technology is yet to become a conventional tool for food industry to develop the healthy and novel food products which can be achieved by multidisciplinary based research approach and consideration of industrial requirements and constraints.

Acknowledgements

None.

Conflict of interest

The author declares no conflict of interest.

References

1. Augustin MA, Sanguansri L. Encapsulation of bioactives. In: Aguilera JM, et al. editors. *Food Materials Science*. New York, USA: Springer; 2007. p. 577–601.
2. Schrooyen PM, Meer RVD, Kruif CG. Microencapsulation: Its application in nutrition. *Proc Nutr Soc*. 2001;60 (4):475–479.
3. Pegg RB, Shahidi U. Encapsulation, stabilization and controlled release of food ingredients and bioactives. In: Shafiur Rahman M editor. *Hand book*

of food preservation. 2nd ed. CRC press, Taylor and Francis group, Boca Raton, USA: FL; 2007. p. 509–568

4. Calvo P, Castano AL, Hernandez MT, et al. Effects of microcapsule constitution on the quality of microencapsulated walnut oil. *Eur J Lipid Sci Technol*. 2011;113(10):1273–1280.
5. Desai K G H, Park HJ. Recent developments in microencapsulation of food ingredients. *Drying Technol*. 2005;23:1361–1394.
6. Boh B, Kardos D. Microcapsule patents and products: Innovation and trend analysis. In: Arshady R, et al. editors. *Microcapsule patents and products*. The MML series, Vol 6, Citus reference series, London, UK; 2003. p. 47–83.
7. Zuidam NJ, Shimoni E. Overview of microencapsulates for use in food products or processes and methods to make them. In: Zuidam NJ, et al. editors. *Encapsulation Technologies for Active Food Ingredients and Food Processing*. Dordrecht, The Netherlands: Springer; 2010. p. 3–29.
8. Zuidam NJ, Heinrich J. Encapsulation of aroma. In: Zuidam NJ, et al. editors. *Encapsulation Technologies for Food Active Ingredients and Food Processing*. Dordrecht, The Netherlands; Springer; 2010. p. 127–60.
9. Gibbs BF, Kermasha S, Alli I, et al. Encapsulation in the food industry: a review. *Int J Food SciNutr*. 1999;50(3):213–224.
10. Atmane M, Muriel J, Joel S, et al. Flavour encapsulation and controlled release-a review. *Int J Food Sci Technol*. 2006;41:1–21.
11. Klinkesorn U, Sophanodora P, Chinachoti P, et al. Stability of spray-dried tuna oil emulsions encapsulated with two-layered interfacial membranes. *J Agric Food Chem*. 2005;53(21):8365–8371.
12. Jeyakumari A, Kothari D C, Venkateshwarlu G. Microencapsulation of fish oil-milk based emulsion by spray drying: impact on oxidative stability. *Fish Technol*. 2014;51:31–37.
13. Jeyakumari A, Kothari DC, Venkateshwarlu G. Oxidative stability of microencapsulated fish oil during refrigerated storage. *J Food Process Preserv*. 2015;39(6):1944–1955.
14. Pratibha K, Kim D, Colin JB, et al. Microencapsulation of omega-3 fatty acids: A review of microencapsulation and characterization methods. *J Fun Foods*. 2014. p. 1–14.
15. Teixeira MI, Andrade LR, Farina M, et al. Characterization of short chain fatty acid microcapsules produced by spray drying. *Materi Sci Engg*. 2004;24(5):653–658.
16. Bennick A. Interaction of plant polyphenols with salivary proteins. *Critical Reviews in Oral Biol Med*. 2002;13(2):184–196.
17. Quideau S, Feldman KS. Ellagitann in chemistry. *Chem Rev*. 1996;96:475–503.
18. Arts IC, Hollman PC. Polyphenols and disease risk in epidemiologic studies. *Am J Clin Nutr*. 2005;81(suppl1):317–325.
19. Scalbert A, Manach C, Morand C, et al. Dietary polyphenols and the prevention of diseases. *Crit Rev Food Sci Nutr*. 2005;45(4):287–306.
20. Manach C, Scalbert A, Morand C, et al. Polyphenols: food sources and bioavailability. *American J Clin Nut*. 2004;79:727–747.
21. Zhongxiang F, Bhesh B. Encapsulation of polyphenols - a review. *Trend Food Sci Technol*. 2010;21(10):510–523.
22. Amr MB, Shabbar A, Barkat A, et al. Microencapsulation of oils: a comprehensive review of benefits, techniques, and applications. *Comp Rev Food Sci Food Safety*. 2015;15(1).
23. Wilson N, Shah NP. Microencapsulation of vitamins-a review. *Asian Food J*. 2007;14(1):1–14.
24. Shabbar A, Chang DW, Khizar H, et al. Ascorbic acid: microencapsulation techniques and trends-a review. *Food Rev Int*. 2012;28(4):343–374.
25. Goncalves A, Estevinho BN, Rocha F. Microencapsulation of vitamin A: a review. *Trends Food Sci Technol*. 2016;51:76–87.
26. Hirotsuka M, Taniguchi H, Narita H, et al. Calcium fortification of soy milk with calcium-lecithin liposome system. *J Food Sci*. 1984;49(4):1111–1112.
27. Cisem T. *Immobilization of thermophilic recombinant esterase enzyme by microencapsulation in alginate chitosan/Cacl$_2$ polyelectrolyte beads*. Izmir, Turkey: Ismir Institute of Technology; 2011. 49 p.
28. Kailasapathy K, Lam SH, Hourigan JA. Studies on encapsulating enzymes to accelerate cheese ripening. *Austr J Dairy Technol*. 1998;53(2):125.
29. Anjani K, Kailasapathy K, Phillips M. Microencapsulation of enzymes for potential application in acceleration of cheese ripening. *Int Dairy J*. 2007;17(1)**:**79–86.
30. Sanders ME. Probiotics: considerations for human health. *Nutr Rev*. 2003;61(3):91–99.
31. Champagne CP, Patrick F. Microencapsulation for the improved delivery of bioactive compounds into foods. *Curr Opin Biotechnol*. 2007;18(2):184–190.
32. Vidhyalakshmi R, Bhakyaraj, Subhasree RS. Encapsulation the future of probiotics-a review. *Adv Biol Res*. 2009;3(3-4):96–103.
33. Erdmann K, Cheung BW, Schroder H. The possible roles of food-derived bioactive peptides in reducing the risk of cardiovascular disease. *J Nutr Biochem*. 2008;19(10):6430–6654.
34. Mohan A, Subin RCK Rajendran, Quan Sophia H, et al. Encapsulation of food protein hydrolysates and peptides: a review. *RSC Adv*. 2015;5:79270–79278.
35. Yeo Y, Namjin Baek, Kinam Park. Microencapsulation methods for delivery of protein drugs. *Biotech Bioprocess Eng*. 2001;6(4):213–230.
36. Pothakamury UR, Barbosa-Canovas GV. Fundamental aspects of controlled release in foods. *Trends Food Sci Technol*. 1995;6(12):397–406.
37. Brannon-Peppas. Properties and application. In: EL-Nokaly MA, et al. editors. *Polymeric Delivery Systems*. ACS Symposium Series 520. Washington, American Chemical Society, USA: DC; 1993. 52 p.
38. Risch SJ. Encapsulation: Overview of Uses and Techniques. In: Risch SJ, et al. editors. *Encapsulation and controlled release of food ingredients*. ACS Symp ser 590, Washington, American Chemical Society, USA: DC; 1995. p. 2–7
39. Azevedo HS, Reis RL. Understanding the enzymatic degradation of biodegradable polymers and strategies to control their degradation rate. In: Reis RL, et al. editors. *Biodegradable Systems in Tissue Engineering and Regenerative Medicine*. USA: CRC Press; 2005. p. 177–201.
40. Fan LT, Singh SK. Controlled Release: a Quantitative Treatment. In: Peppas NA editor. *Polymer properties and Applications*. Vol 13, Berlin, Germany: Springer-Verlag; 1989. 250 p.
41. Rosen RM. Delivery system handbook for personal care and cosmetic products. *Technology, applications and formulations*. New York: USA: William Andrew; 2006. 1095 p.
42. Hickey DK, Kilcawley KN, Beresford TP, et al. Lipolysis in cheddar cheese made from raw, thermized, and pasteurized milks. *J Dairy Sci*. 2007;90(1):47–56.
43. Frascareli EC, Silvaa VM, Tonon RV, et al. Effect of process conditions on the microencapsulation of coffee oil by spray drying. *Food Bio prod Process*. 2012;90(3):413–424.

44. Toldra F, Reig M. Innovations for healthier processed meats. Trend. *Food Sci Technol*. 2011;22(9):517–522.

45. Park D, Maga JA. Identification of key volatiles responsible for odour quality differences in popped popcorn of selected hybrids. *Food Chem*. 2006;99(3):538–545.

46. Wong SW, Yu B, Curran P, et al. Characterizing the release of flavor compounds from chewing gum through HS-SPME analysis and mathematical modeling. *Food Chem*. 2009;114(3):852–858.

Citation: Jeyakumari A, Zynudheen AA, Parvathy U. Microencapsulation of bioactive food ingredients and controlled release-a review. *MOJ Food Process Technol.* 2016;2(6):214–224. DOI: 10.15406/mojfpt.2016.02.00059