Microencapsulation: An overview on concepts, methods, properties and applications in foods

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Abstract
Microencapsulation is an advanced food processing technology, using which any compound can be encapsulated inside a particular material, making a tiny sphere of diameter ranging from 1 μm to several 100 μm. Microencapsulation is done for protecting the sensitive compounds and, hence, ensuring their safe delivery. The compound or active material which is encapsulated is called the core and the material which is used for encapsulating is called the encapsulant. Encapsulants can be either polymeric or nonpolymeric materials like cellulose, ethylene glycol, and gelatin. There are several techniques used for microencapsulation. Fluidized bed coating, spray cooling, spray drying, extrusion, and coacervation are few to be named. The selection of a particular technique depends upon the properties of the core material, encapsulant, and different properties and morphology of the capsules desired. The characterization and optimization of efficient and successful encapsulation can be done by studying the encapsulation efficiency and various properties of the capsules like morphology, size, hydrophobicity, hygroscopicity, solubility, surface tension, thermal behavior, and mechanical properties. Microencapsulation is a technology that is extensively used in foods, whether as a fortifying tool or as a mode for the development of a functional food. Based on the fundamental understanding of encapsulation and latest research and findings from literature, this review critically analyses and brings together the utilization of this particular technique in foods, different methods used for encapsulation, different properties of the capsules which result from the different techniques adopted for microencapsulation and different release mechanisms used for delivering the compounds.

KEYWORDS
core, encapsulant, functional food, hydrophobicity, hygroscopicity, matrix, mechanical, microencapsulation, surface tension

1 | INTRODUCTION

Microencapsulation is an emerging technology that leads to the protection of different food components or functional constituents against various processing conditions by covering them inside a polymeric or nonpolymeric material and allowing their controlled release under particular conditions. In addition, it enhances the sensory quality by masking the unpleasant taste, aroma, and flavors; also, it increases food
safety by inhibiting the growth of the microbes (Hasanvand et al., 2015; Sengupta et al., 2001). Different bioactive compounds, such as omega-3 and omega-6 fatty acids, vitamins, phenolic compounds, and carotenoids are now widely used to develop products with numerous functional properties to meet up the increasing consumer demands. However, such compounds are highly unstable under certain conditions of light, temperature, pH, and oxygen. Therefore, microencapsulating such compounds is a mode of protecting them from such harsh conditions during processing of foods. Several food constituents which are widely encapsulated include different flavoring agents, lipids, antioxidants, essential oils, pigments, probiotic bacteria, and vitamins (Azeredo, 2005). Different coating materials are used depending on their rheological properties, their ability to disperse the active compound and stabilize it, inertness towards the active compound and their ability to properly hold the active compound. Some coating materials include carbohydrates such as starch, maltodextrin, modified starch, cyclodextrin, cellulose; lipids such as wax, paraffin, beeswax, diacylglycerols; gums such as gum acacia, agar, carrageenan; and proteins such as gluten, casein, and gelatine.

Microencapsulation is a technology that serves as a tool to protect the sensitive and expensive nutrients (Meyers et al., 1998), by providing them with a protective wall, which allows them to get released at a particular site, at a particular time, and under particular conditions. For example, as mentioned by Gudas et al. (2000), in chewing gums, the encapsulated flavors escape only on chewing. In the recent past, complex food formulations have been demonstrated in the food industries like the use of certain volatile flavors in instant mixes, fatty acids in the dairy products, which are highly prone to auto-oxidation. Here, microencapsulation can come to rescue (Gharsallaoui et al., 2012; Khan et al., 2011). Large number of techniques for microencapsulation include spray chilling, spray cooling, fluidized bed coating, liposome entrapment, extrusion, freeze drying, and coacervation.

On the basis of the physical and the chemical properties of the core, composition of the shell material and the microencapsulation method used, various types of capsules are obtained: simple sphere surrounded by the wall material, capsules with irregular core, multiple distinct cores within a continuous coating of wall material, multiwalled microcapsules and core particles embedded within the matrix of wall material. Depending on the kind of coating material used, different techniques are used to produce the microcapsules and these techniques lead to differences in the properties of the capsules like capsule size, morphology, porosity, hygroscopicity, hydrophobility, surface tension, and thermal behavior. It is very important to learn about these properties of the capsules, so as to understand their behavior in any food system. These properties in turn are closely related to the controlled release of the encapsulated core. The core material needs to be properly protected to be released at a specific time, thus improving the efficacy of the microencapsulation process and leading to the broad range of applications. The major factors influencing core release includes nature of the core material, the ratio of the core and the encapsulant, nature of the encapsulant, and the interaction between the two (Roberts & Taylor, 2000). This review critically analyses all the important concepts associated with microencapsulation including the need of microencapsulation in food, properties of the coating materials, and the type of core material they can be used for. Furthermore, it also includes different techniques of microencapsulation, properties of the microcapsules like physical, mechanical, thermal, and functional and different core release mechanisms. It also showcases the relevance of this technology in food industries.

## 2 NEED FOR MICROENCAPSULATION IN FOODS

### 2.1 Protection and improved delivery

Many components, like the essential oils, having numerous benefits like antimicrobial and antioxidant properties, the microorganisms which are used in fermentation and the probiotics, can widely be used in the preparation of functional foods. But components like these are highly susceptible to oxidation when exposed to high temperature, light or oxygen atmosphere. So, encapsulation has proved to be one stop solution for such problems. Piletti et al. (2019) encapsulated garlic oil by using β-cyclodextrin as a method of thermal protection for its antimicrobial action. The study reported that encapsulation increased the thermal stability of garlic oil. Similar work was reported by Girardi et al. (2016), where *Peumus boldus* oil was encapsulated by coacervation method and incorporated in germinating peanut seeds to protect them against fungal pathogens. Mirzaei et al. (2012) encapsulated strains of *Lactobacillus Acidophilus* within a mixture of resistant starch and calcium alginate gel, using extrusion, which resulted in increasing survival rate of the strains in Iranian cheese, even after storing for 6 months. Yuliani et al. (2006) demonstrated that encapsulation of limonene within β-cyclodextrin using extrusion proved to be an effective way to protect limonene from getting oxidized. Hence, these studies prove that microencapsulation is an effective method for protecting different sensitive components.

Improved delivery of the components being encapsulated means that these components are being delivered completely upon their controlled release and this is based on choosing the right coating material for encapsulation. González-Ferrero et al. (2018) used soybean protein-based coating material for improved delivery of probiotics in the gut. The idea was to study the efficacy of soybean protein-based coating material in protecting the probiotics from stress conditions like low pH and enzymes of simulated gastric fluid. Two different strains were selected for encapsulation, namely *Lactobacillus plantarum* CECT 220 and *Lactobacillus casei* CECT 475. The viability of the strains was studied under in vitro gastrointestinal conditions and it was found that the soybean protein concentrate was effective in enhancing the viability of the probiotic strains and protecting them from gastrointestinal fluids.

### 2.2 Controlled release

Encapsulated functional components like certain vitamins, flavors, or essential oils when incorporated in the food matrix are of importance...
TABLE 1  Coating materials, their sources, properties, and the techniques they are suitable for

| Coating material | Source | Properties | Techniques used |
|------------------|--------|------------|-----------------|
| **Gums** | Gum Arabic, sodium alginate, Carrageenan | Form soft elastic gels, poor tensile strength, hydrocolloidal | Extrusion, phase separation Spray drying, coacervation, emulsification |
| **Carbohydrates** | Starch, dextran, sucrose | Hydrocolloidal, comparatively higher tensile strength than gums | Spray drying, fluidized bed coating, extrusion, freeze drying |
| **Proteins** | Gelatin, albumin | Emulsification, gelation, foaming, and water binding capacity | Spray drying, extrusion, coacervation, freeze drying emulsification |
| **Lipids** | Bees wax, stearic acid, Phospholipids | Plasticizing properties, Good barrier to gases and water vapor | Fluidized bed coating, spray chilling/cooling, extrusion |
| **Celluloses and their derivatives** | Plant cells | Hydrophilic, good film forming ability and surface activity | Spray drying, fluidized bed coating, extrusion, emulsification/precipitation Coacervation |
| **Chitosan** | Shells of crustaceans | Good barrier to gases and water vapor | Spray drying, coacervation, emulsification |

Ref: Goud and Park, 2005.

only when they are released at a particular location in the body or at a particular time, for example, encapsulated flavors in chewing gum are released only when the gum is chewed. In this regard, the type of shell material used plays an important role. There are different mechanisms by which the encapsulated components can be released from the capsules. These include: (a) burst-release mechanism, this is basically used in case of encapsulated probiotics, (b) thermal degradation, where the coating material degrades at a particular temperature and the core is released and few others, which are described further in the other section. Basu et al. (2018) encapsulated L. casei in alginate matrix and reported its controlled release in a food matrix. The probiotic beads formed were suspended in coconut water fortified with lactose. In this medium, the entrapped cells grew and when the number of cells increased up to a critical concentration, consequently the beads burst and the microbes were released. So, in this case, encapsulated microbes were provided with favorable environment for their growth, hence, making the beads encapsulating them burst. Wang et al. (2019) reported controlled release of allyl methyl disulphide, a lipophilic compound in garlic during cooking. This compound is highly volatile in nature, so it was trapped in a biopolymer gel made out of complex formed between calcium ion and sodium alginate. Entrapment of the compound in a biopolymer gel delayed the flavor release up to three-folds during cooking, hence, releasing it at a later stage of cooking.

study showed that the bitter taste of mussel protein hydrolysate could be successfully masked by encapsulating it by spray drying using modified starch and maltodextrin as the carrier agents. Similarly, unpleasant odor and taste of isoflavones were masked by microencapsulating them using maltodextrin and inulin (Wyspianska et al., 2019).

3 | COATING MATERIAL

The coating material or the wall material used in microencapsulation should be such that it is able to form a cohesive film on the core, stabilize it, and provide strength to the capsules, inert, so that it has no reaction with the core material, does not provide any specific taste to the product, impermeable and with ability to release the core at a specific time and place, upon specific treatment.

Table 1 shows different types of coating materials, their sources, properties and techniques in which they can be used.

4 | AN OVERVIEW OF MICROENCAPSULATION TECHNIQUES

4.1 | Spray drying

Spray drying is a technique in which a feed solution, which is a mixture of the core material and the wall material is atomized and formed into a mist inside a chamber, where hot air is applied to convert the mist into powder. Depending on various factors like the characteristics of the feed solution and operating conditions, powder of varied particle size can be produced. In spray drying, the core material, that is, the material of interest gets trapped in the dried powder. Some of the advantages of this method: it can be used for different encapsulating
agents, it is economical, flexible, can be used for many different types of materials and can be scaled up easily. Many studies have shown successful implementation of this technique in encapsulation. Cardamom Oleoresin was encapsulated within a mixture of maltodextrin, modified starch, and gum Arabic using spray drying and the results showed increased protection of oleoresins (Krishnan et al., 2005). Bayram et al. (2005) reported successful encapsulation of sumac flavor in sodium chloride using spray drying.

Although spray drying is one of the most extensively used methods for microencapsulation and has many stated advantages also, some studies have portrayed certain drawbacks of the technique. Fang et al. (2006) reported that when hot air is used as a drying medium for encapsulation of omega-3 fatty acids, dried powder has particles with highly porous structure, making the powder more prone to oxidation, thus, reducing the shelf life. Similar results were reported by Kolanowski (2005), while developing spray dried fish oil powder. Thus, it can be said that the same method can be effective for encapsulating one kind of material, while having drawbacks for some other kind of materials.

4.2 Spray cooling

Spray cooling method of encapsulation is very similar to spray drying in operation, the major difference being the use of cold air in it. Here, a mixture of core material and wall material is atomized to form a mist inside a chamber, inside which cold air flows. The low temperature within the chamber results in solidification of the micro droplets, leading to the formation of microencapsulated powder. This technique also has a huge potential in scaling up. Some successful implementations of this technique in encapsulation includes, microencapsulation of tocopherols within lipid matrix, with encapsulation efficiency as high as 90% (Gamboa et al., 2011), encapsulation of iron, iodine, and vitamin A within hydrogenated palm oil to fortify salt, where in the microcapsules formed were highly stable (Wegmüller et al., 2006).

However, this method also has some documented drawbacks. Some studies have shown that the microcapsules formed by spray cooling are not very stable and it leads to expulsion of the core material during storage (Jenning et al., 2000; Müller et al., 2002).

4.3 Coacervation

Coacervation is a simple technique which involves formation of a homogeneous layer of the polymeric wall material around the core material. This is achieved by altering the physicochemical properties of the wall material by change in temperature, pH, or ionic strength. Here, the core material and the wall material are mixed to form an immiscible solution. Then, phase separation is carried out by changing the ionic strength, pH, or temperature to form coacervates, which are tiny liquid droplets, consisting of polymer-rich dense phase. These coacervates then surround the core material, forming the microcapsules. Electrostatic interaction between two aqueous media is responsible for liquid to gel transition, that is, ionic gelation, hence, leading to the formation of coacervates. This technique is basically used for encapsulating hydrophilic molecules. Such coacervation, which involves only one polymeric material is called simple coacervation. One example of such a polymer can be sodium alginate. In simple coacervation, sodium alginate is dissolved in water and the active compound that needs to be encapsulated, which is usually an oil, is mixed into it and the emulsion formed is released in drops into a gel-forming media like calcium chloride. Ionic interaction between sodium alginate and calcium chloride leads to formation of insoluble polymers, calcium alginate. Several studies have been reported showing successful use of this technique in microencapsulation. Sweet orange oil was encapsulated by Jun-xia et al. (2011) by coacervation using soybean protein isolate (SPI) as the wall material. Coacervation can also involve more than one polymer, then it is called complex coacervation. One common example of complex coacervation includes polymers, gelatin, and alginate. Gelatin is solubilized in water at an acidic pH for obtaining positive charges and alginate is solubilized in water separately at a basic pH to obtain negative charges. The active compound to be encapsulated is mixed into the alginate solution and homogenized properly. This alginate phase is then mixed intensively with the gelatin phase and the temperature is raised until chemical reaction between alginate and gelatin starts. The active compound gets encapsulated by the formation of polycationic-polyanionic insoluble polymer around it. Liu et al. (2010) used complex coacervation method for encapsulation and stabilization of flaxseed oil. Here, gelatin and gum Arabic, the two oppositely charged polymers were used as the wall materials and the deposition of these coating materials around the core was initiated by changing the pH of the medium. However, the use of this method is limited as it best works only within a certain pH range and with certain electrolyte and colloidal solutions.

4.4 Fluidized bed coating

Fluidized bed coating is an encapsulation method in which coating material is sprayed onto the fluidized core material. Here, the core material is fluidized by application of air, onto which a coating material is sprayed. Different fluidized bed coating methods are: (a) Top spray (b) bottom spray, and (c) tangential spray. In this method of encapsulation, coating efficiency of the wall material is dependent on various parameters like feed rate of the wall material, atomization pressure of the nozzle, inlet air temperature, and velocity, etc. Coronel-Aguilera & San Martín-González (2015) encapsulated spray dried beta carotene with hydroxypropyl cellulose using fluidized bed coating. Here, temperature and feed rate of hydroxypropyl cellulose was varied to determine how these factors effected the film forming ability of the coating material and, hence, the stability of beta carotene during storage.

4.5 Extrusion

Extrusion technology for microencapsulation can be used for producing highly dense microcapsules. To use this method, the core and the
### TABLE 2  Microencapsulation process, principle and nature of core material

| Microencapsulation process | Principle                                                                 | Nature of core material |
|----------------------------|---------------------------------------------------------------------------|-------------------------|
| Spray drying               | Formation of emulsion or dispersion and atomization of mixture into the drying chamber | Solids and liquids       |
| Spray cooling              | Dispersing of the core into a liquefied shell material and spraying it through a heated nozzle into a controlled, cold environment | Solids and liquids       |
| Fluidized bed coating      | Solid or powdered particles of core material are suspended in an open stream of air and coated with molten polymer. | Solids                  |
| Coacervation               | Formation of three immiscible chemical, Deposition of coating, Rigidization of coating | Solids and liquids       |
| Coextrusion                | Involves passing an emulsion of core and wall material through a high pressure die Mixture is extruded in a cold solvent bath as pellets | Solids                  |
| Emulsification             | Formation of an emulsion of the core and the wall material and stabilization of the emulsion by adding an emulsion stabilizer. | Solids and liquids       |
| Cyclodextrin Inclusion     | Hydrophobic interaction between the cyclodextrin surface and the guest compounds. | Solids and liquids       |

Wall material should be immiscible. Here, the core and the wall materials are passed in such a way that the wall material surrounds the core and they are passed through concentric nozzles, thus, forming droplets containing the core surrounded by the wall material. Then solidification is done either by cooling or using an appropriate gelling bath wherein the droplets fall and solidify due to formation of complex. The encapsulates formed using this method are relatively larger in size than formed using any other method and also, this technology is useful with limited wall materials.

#### 4.6 Emulsification

Encapsulation using emulsification technique is done by dispersing the core in an organic solvent, containing the wall material. The dispersion is then emulsified in the oil or water, to which emulsion stabilizer is added. Encapsulation of the core occurs by formation of a compact polymer layer around it, by evaporation of the organic solvent. This is one of the frequently used techniques of encapsulation as the procedures involved are very simple. This technique is widely used for encapsulating enzymes and microorganisms. Song et al. (2013) reported encapsulation of probiotics in alginate-chitosan using emulsification and demonstrated better resistance of the probiotics under stimulated gastrointestinal conditions.

#### 4.7 Cyclodextrin inclusion

Cyclodextins are cyclic oligosaccharides, capable of forming inclusion complexes with many organic compounds. Cyclodextins have an internal nonpolar cavity and hydroxyl groups on the surface. Formation of inclusion complexes of cyclodextins with the hydrophobic compounds mainly takes place by the hydrophobic interaction between the cyclodextrin surface and the guest compounds. However, other forces, such as dipole-dipole interactions and van der walls forces, may also be involved in the formation of the complexes (Rakmai et al., 2018). There are several methods for obtaining inclusion complexes with cyclodextrin. Some of them are: (a) Coprecipitation method, which is used for the nonwater-soluble substances. In this method, the compound to be encapsulated is dissolved in organic solvents like benzene, chloroform, diethyl ether, etc. and to this solution, cyclodextrin dissolved in water is added in appropriate amount with proper agitation. The solution is then cooled for obtaining the complex crystals. Finally, the crystals are washed using an organic solvent and dried. (b) Freeze drying or lyophilization: this method is mostly used for thermolabile compounds. Appropriate amount of cyclodextrin and the compound of interest are dissolved in water by proper stirring. The solution is then freeze dried and the powder obtained is washed with an organic solvent and dried under vacuum. (c) Spray drying: this method is used only for the thermostable molecules. Cyclodextrin and the compound to be encapsulated are dissolved in deionized water. And the solution is dried in a spray dryer. In many food-related applications, cyclodextins are used for encapsulation of flavor compounds, as they provide better retention, protection, and enhance controlled release. Furuta et al. (2008) explained in detail, the entrapment of food flavors in cyclodextins, using freeze drying and spray drying. Different modified cyclodextins, namely 2-hydroxypropyl-β-cyclodextrin, randomly methylated β-cyclodextrin and triacetyl β-cyclodextrin were used for the inclusion of flavors, namely, d-limonene, allyl isothiocyanate, and l-menthol. Inclusion of flavors in cyclodextrin was done by preparing solutions, which were then spray dried or freeze dried. Depending on the solubility of the cyclodextrin, different mediums were used for encapsulation.

Some of these techniques, along with their principles and type of core material they are used for are represented in Table 2 and Figure 1 shows diagrammatic representation of different microencapsulation techniques.
5 | DIFFERENT PROPERTIES OF THE CAPSULES

5.1 | Physical properties

5.1.1 | Particle size and morphology of microcapsules

The particle size of the microcapsules depends on the different techniques which are used to produce the microcapsules. Table 3 shows the variation in the particle sizes due to different techniques used. Morphology of the microcapsules refers to the internal as well as the external structure of the capsules which largely depend on the operating conditions that are used to produce the microcapsules as well as the wall materials used. Different types of capsules can be obtained—simple sphere surrounded by the wall material, capsules with irregular core, multiple distinct cores within a continuous coating of wall material, multiwalled microcapsules and core particles embedded within the matrix of wall material, as shown in Figure 2.

Morphology can be determined by Scanning Electron Microscopy (SEM). By using SEM, both internal as well as external microstructures can be obtained. According to Carneiro et al. (2013), while observing the external morphology of the microcapsules containing flaxseed oil surrounded by different shell materials like gum arabic, obtained using spray drying technique, the particles showed varied sizes, a
**TABLE 3** Relative size of microcapsules formed corresponding to microencapsulation process

| Microencapsulation process   | Approximate particle size (μm) |
|------------------------------|---------------------------------|
| Spray drying                 | 5-5000                          |
| Extrusion                    | 250-2500                        |
| Coacervation                 | 2-1200                          |
| Fluidized bed coating        | 20-1500                         |
| Phase separation             | 0.5-1000                        |
| Rotating disk                | 5-1500                          |
| Solvent evaporation          | 0.5-1000                        |
| Sol-gel encapsulation        | 2-20                            |
| Layer-by-layer (LBL)         | 0.02-20                         |

**FIGURE 2** Different types of microcapsules: (a) monolayer; (b) multilayer; (c) matrix; (d) multicore; (e) irregular

Typical characteristic of particles obtained using spray drying. Moreover, the particles obtained were spherical in nature with no observed fissures on them, which implied that particles were less permeable to gases and retained most of the active material. Similar results were obtained by Trindade and Grosso (2000). However, sometimes capsules may also develop roughness on their surface during spray drying. And such imperfections are developed when the film formation process during drying of atomized droplets slows down. In a similar way, internal morphology was analysed and it was observed that the microcapsules obtained were hollow and the core material was stuck onto the surface, which is also a characteristic of particles obtained using spray drying. Differences in wall material also affected the topography of the microcapsules formed. Similarly, Dong et al. (2011), while studying about the microcapsules with peppermint oil as the core material, produced by complex coacervation method reported that multinuclear microcapsules were formed with many emulsion droplets being encapsulated by coacervates. SEM results also showed that microcapsules were spherical, with their surface being smooth and continuous. Likewise, on the basis of the technique and the core and the wall material used, morphologies of microcapsules differ.

### 5.1.2 Porosity

Porosity of the microcapsules, formed using any technique, is one of the most important properties of the microcapsules, responsible for their function in a particular food matrix. And this property is greatly dependent on the composition of the wall material of the microcapsule and the technique which is used to produce the microcapsule. Wall matrix, which holds the core is designed in such a way so as to direct the mass transfer between the environment and core (Rosenberg et al., 1985; Jackson & Lee, 1991; Shahidi & Han, 1993). The porosity of the wall material plays a great role in controlling the permeation of volatiles within the capsule (Arshady, 1993; Dziezak, 1988). It also determines the oxidative stability of the core of the microcapsule by controlling the permeation of oxygen through it. In case of volatile cores, wall permeability is a major factor for increasing the chances of core loss during storage (Rosenberg et al., 1985). Moreau and Rosenberg (1999) examined the porosity of the spray-dried microcapsules, encapsulating anhydrous milk fat within the mixture of lactose and whey protein as wall system by using gas displacement pycnometry. In this study, helium and nitrogen were used as the permeating gases. Results showed the differences in the way of penetration of helium and nitrogen through the microcapsules. It was seen that helium could fill all the accessible volume very fast, while penetration of nitrogen was comparatively slower. Overall, the results of gas-displacement pycnometry indicated the presence of pores characterizing both, anhydrous milk fat containing and core-free microcapsules (Rosenberg et al., 1985). The microcapsules containing milk fat were found to be more porous than the ones, which were free from the core material. Similar characteristics were obtained for the microcapsules encapsulating fish oil with dextrin and sodium caseinate wall materials. Those microcapsules also exhibited molecular-sieve kind of porosity, that is, with pores, which are minute enough to prevent the entry of molecules. Likewise, Allan-Wojtas et al. (2008) also reported the study of calcium alginate microcapsules, encapsulating probiotic bacteria. For studying the microstructure of the capsules, cryo-Scanning Electron Microscopy (cryo-SEM) and Transmission Electron Microscopy (TEM) were used. SEM results revealed the differences between the structure of bacteria containing and the core-free capsules. The bacteria containing capsules were found to be more porous as compared to the core free capsules, hence attributing to the fact that the bacteria interfered with the formation of cross linking of the alginate with calcium chloride, as described by Truelstrup Hansen et al. (2002) and Sultana et al. (2000). TEM analysis also showed the similar results. Hence, for determining the porosity of microcapsules, gas displacement pycnometry and electron microscopy, both can prove to be very important tools for analyzing the microstructure of the
capsules, useful for designing the carrier substances for a particular core material.

5.1.3 Surface hydrophobicity

Surface hydrophobicity can be defined as a physical property of a molecule that is repelled by water. This is a property which is largely based on the core material to be encapsulated and the wall material. In a study by Mendanha et al. (2009), microcapsules were produced encapsulating casein hydrolysate within SPI and pectin, the results showed that hydrophobicity decreased with the increase in the concentration of casein hydrolysate in the formulation of the microcapsule. With the increase in casein concentration, more and more hydrophobic interactions were formed with SPI, thus, leading to the turning of the hydrophobic groups from SPI to the core of the capsules, which in turn causes reduction in hydrophobicity. In another study by Beaulieu et al. (2002) and Floury, Desrumaux et al. (2002), it was found that globular proteins like soy and whey protein, which were used as wall materials, formed soluble aggregates through surface hydrophobic interactions after high pressure treatment. Hence, it can be seen that surface hydrophobicity is a very critical physical parameter which needs to be considered, while selecting the shell material for encapsulation, as shell material properties have a huge impact on the hydrophobicity of the microcapsules.

5.1.4 Flow properties

Flow properties of the microencapsulated powders include bulk density, tapped density, porosity, and compressibility. Analysis of bulk density and tapped density of the capsules is important in order to obtain the capacity of the powder formed, in packaging, storage, and the distribution process. Bulk density is dependent on the particle density, size, shape, and water content of the microcapsule (Shamaei et al., 2017), which in turn depends on the coating material and technique used for encapsulation. Dependence of bulk density on the coating material has been explained by Mehyar et al. (2014) in a study, where cardamom essential oil was encapsulated using whey protein isolate (WPI), guar gum and carrageenan by freeze drying. Bulk density of the microcapsules was highest when WPI was used alone as the coating material as compared to combination of WPI with guar gum and carrageenan. In a study by Hermanto et al. (2016), bulk density of cinnamon oil microcapsule, encapsulated within a coating of maltodextrin and gum arabic at different concentrations, was measured using a very common method of tapping, which is also reported in Chinta et al. (2009). And it was found that if the size of the microcapsule formed is small, it would lead to larger mass density of the capsule due to decrease in the cavities between the particles. Also, higher levels of water leads to increase in the weight of the material in the container, volume remaining the same, thus, causing an elevation in the bulk density (Prabowo, 2010). Dependence of bulk density on the technique used can be observed from the results reported by Shame et al. (2017). Herein, walnut oil was microencapsulated using spray drying technique and the results revealed that with the decrease in feed atomization pressure and increase in the inlet air temperature, the bulk density of the microcapsules decreased. This was because, with the increase in inlet air temperature, microcapsules with hollow structure and high sphericity were formed. Similar results were also reported by Tonon et al. (2011).

Flowability of microencapsulated powder formed is determined by using two parameters, percent compressibility or Carr’s Index and the Hausner Ratio (HR), as reported by Turchiuli et al. (2005). Similar methods were adopted by Xue et al. (2013) for determining the flowability of the lycopene microcapsules. The higher value of HR attributed to the fact that the powder was cohesive, indicating high powder viscosity and was restricted to free-flow. Flowability largely depends on the particle size and particle size distribution of the microcapsules, which in turn is influenced by other factors like shape and surface roughness of the microcapsules. Thus, it is very crucial to choose a particular wall material and a particular technique of encapsulation to obtain the flow properties of the capsules as desired.

5.2 Micromechanical properties

Mechanical trigger of the microcapsules depends upon their micromechanical properties. It is a fundamental need to study the mechanical properties of the microcapsules once they are produced, so as to ensure that the release of the core material takes place at a specific target and at a specific time and not before that. More specifically in many food applications, a very adjustable kind of mechanical strength is desired in the microcapsules. The mechanical properties of the microcapsules include elastic modulus, rupturing force that is required to rupture the capsule and nominal rupture stress, which is equal to the rupture force divided by the initial cross-sectional area of the microcapsule (Sagis, 2015). And these largely depend on the core to shell ratio in capsule and also on the preparation and processing conditions, for instance, different polymerization temperatures and time and difference in the drying methods like oven drying, spray drying, or fluidized bed drying. The mechanical properties of the microcapsules also depend upon the type of capsules formed, like whether they are multiwalled or single-walled type. For example, there is this new technique called layer-by-layer (LBL) deposition of the shell material, which involves adsorption of different biopolymers like polysaccharide and certain protein fibrils in alternate layers, wherein the former is flexible and the latter is stiff, leading to properties of the capsules, which are application specific. In such a technique, mechanical strength of the capsules depend on the number of layers adsorbed and also on the flexibility and rigidity of the biopolymers. Numerous methods for characterizing the mechanical properties of the microcapsules made up of polymeric materials are evolving, so the first task which comes in here is to find out the potential as well as the limits of different techniques.

The methods for determining the mechanical properties of the shell are either tested on the microcapsule itself or on the macroscopic surfaces. The methods for characterizing the macroscopic surfaces, that is, microcapsule population, include compression between the plates
Figure 3  Microcompression of a single capsule: (a) probe centered above the capsule; (b) probe displaced; (c) probe getting displaced leading to buckling of the shell

and the osmotic pressure test. Whereas methods for characterization of single microcapsules include Atomic Force Microscopy, micropipette aspiration, and micromanipulation. Some of these methods are discussed in the following section.

a. Colloidal foam Atomic Force Microscopy (AFM)

Colloidal foam Atomic Force Microscopy (AFM) method basically involves microcompression of a single particle (Sagis, 2015). Herein, the capsule under consideration is allowed to adsorb onto a substrate, which is then deformed by a colloidal probe particle attached to a cantilever AFM, as shown in Figure 3. The probe particle compresses the microcapsule by itself getting displaced in a vertical direction over a distance d. The force required for displacement of the probe particle over a distance d can be calculated from the known force constant of the cantilever and the deflection it undergoes, which is determined by a laser. So, a force displacement curve can be generated, which in turn can be analyzed by using an appropriate model to determine the mechanical properties of the capsule (Fery & Weinkamer, 2007; Neubauer et al., 2014).

b. Fluid-mechanics-based determination of mechanical properties

Mechanical properties of the microcapsules can be determined by applying extensional and shear force on them in flowing fluid (Sagis, 2015). Rotating shear devices are used for this purpose, as shown in Figure 4. These rotating shear devices have transparent concentric cylinders with narrow gap between them, in which a very dilute dispersion of the microcapsules is being poured. The microcapsules in the dispersion are deformed in such a way that they form an angle with the flow direction, once the dispersion gets exposed to a steady shear field. The degree of deformation as well as the orientation of the microcapsules gives their mechanical characterization.

c. Osmotic swelling method

For microcapsules having water permeable shell and aqueous core, their mechanical characterization can be done by using this method (Sagis, 2015). In this method, the microcapsules are made to come in contact with an aqueous high molecular weight polymer with a continuous phase. Difference in osmotic pressure between the interior and the exterior phase is created due to difference in the chemical potential of water between the two phases. And when the concentration of the external polymer is very high, migration of water starts taking place from the interior aqueous phase to the exterior one, until equal chemical potential is reached on both the sides. As a result of this movement of water, there is a shrinkage in the capsule, leading to the crumpling of the shell, as shown in Figure 5. In order to observe such a phenomena, laser microscopy is used. The critical osmotic pressure required for crumpling is determined and the shell characterization is done by plotting this critical pressure versus the wall thickness of capsule.

d. Method based on thermal expansion

This method is used for mechanical characterization of the microcapsules with an oily core. It is valid only when the coefficient of thermal expansion of the core material is more than that of the shell material as well as the continuous phase in which the capsules are dispersed. In this technique, capsules are dispersed in a continuous phase and they...
are observed under a microscope with a thermal stage. The dispersion is subjected to a temperature that is continuously increasing at a fixed rate. The core of the capsule expands more than that of the shell and the continuous phase, which leads to the building up of stress inside the capsule. This continues until the shells burst. This process is shown in Figure 6. Once the 90% of the capsules are burst, temperature as well as the time required for bursting is recorded. Use of this technique is reported by Humblet-Hua, van der Linden, and Sagis (2012) for shell characterization of the microcapsules having shells reinforced with lysozyme fibrils, which were produced by using LBL adsorption. No such studies have been reported in the food microcapsules.

5.3 | Thermal properties

Thermal properties of microcapsules is one of the crucial properties to be studied so as to determine their storage stability as well as the release rates. These can be obtained by a technique called Differential Scanning Colorimetry (DSC). In this technique, there are separate holders for sample and a reference in the instrument. Heaters are present which either increase the temperature at a specified rate or holds the colorimeter at a given temperature. The instrument measures the heat flow difference between the reference and the sample. Xie et al. (2010) studied the thermal properties of the microcapsules encapsulating vitamin A within starch octenyl succinate using DSC. From the DSC curve, an endothermic transition was observed which attributed to the glass transition. The glass transition temperature ($T_g$) of the microcapsule from the DSC thermogram was seen to be 56.355°C with the specific heat of 0.377 J/g. $T_g$ value has a relation to the amorphous structure, which suggests that, at $T_g$ value, a substance changes its state from glassy to rubbery substance (Lim, Chang, & Chung, 2001; Xie et al., 2010). Below the $T_g$ value, the movement of molecular chain segments was found to be poor, which indicated better protection ability to the core material. $T_g$ value being 56.355°C, was greater than the normal storage temperature (25°C), which indicated good storage stability of vitamin A microcapsules when stored at room temperature in a glassy state. Thus, DSC results revealed that the glass transition temperature ($T_g$) and the melting temperature ($T_m$) were 56.355 and 208.300°C, respectively, which showed that the vitamin A microcapsules had the storage and heating stability. It can be clearly observed from the above mentioned study that determination of thermal properties of the capsules is crucial for indication of correct storage temperature and also the indication of the temperature at which the food containing the microcapsules needs to be processed.
TABLE 4 Functional properties of different microcapsules

| Core material | Encapsulant | Properties of microcapsules | References |
|---------------|-------------|----------------------------|------------|
| Fish oil      | Sodium caseinate and casein hydrolyzate | Oxidative stability | Drusch et al. (2012) |
| Ellagic acid  | Soybean lecithin liposomes | Controlled release | Madrigal-Carballo et al. (2010) |
| Hesperetin    | Chitosan, lipids | Stability, improved solubility and better sensory properties | Fathi, Varshosaz et al. (2013) |
| Vanillin      | Polyvinyl alcohol | Temperature stability, controlled release | Kayaci and Uyar (2012) |
| β-carotene    | Casein | Heat stability, controlled release, cold water solubility | Sáiz-Abajo et al. (2013) |
| Resveratrol   | Chitosan and β-cyclodextrin derivative | Controlled release, light stability and better water solubility | Zhang, et al. (2013) |
| Lycopene      | Cyclodextrin | Oxidative stability and controlled delivery | Xue et al. (2013) |

5.4 Functional properties

In addition to the physical, mechanical, and thermal properties of the microcapsules, functional properties are also very important, especially while using the microcapsules to develop a new product with added functional properties. Following are some of the important functional properties of the capsules. Different functional properties of various microcapsules, encapsulating different compounds are shown in Table 4.

5.4.1 Solubility

Solubility evaluation of the microcapsules is basically done to determine the behavior of microcapsules in water or any other medium, that is, whether the core material is released in that medium or not. Solubility is a property of microcapsules, which is attributed to the type of wall material used for encapsulation as well as the technique used for production of the microcapsules. In a study performed by Mendanha et al. (2009), solubility of the microcapsules, containing casein hydrolysate within Soybean Protein Isolate (SPI) and pectin was very low, even after soaking in water for 24 h. This confirmed that the method i.e. coacervation for producing the microcapsules as well as the encapsulating agents used led to the production of the microcapsules, which are very stable in the aqueous medium as well as which have favorable controlled release properties. The findings in this paper leads to the conclusion that solubility also depends on the concentration of the core material that is used for encapsulation as here, the solubility increased progressively with the increase in the concentration of casein hydrolysate in the microcapsules. Such results were attributed to the fact that encapsulation efficiency diminished with increasing levels of casein hydrolysate.

5.4.2 Surface tension

Surface tension is basically defined as the property of a fluid surface to behave as a stretched elastic membrane. The cohesive forces or the interfacial forces on the fluid membrane are responsible for this phenomenon. The interfacial forces govern phenomena like wetting of solids by liquids (Atwood & Florence, 2003). Mendanha et al. (2009) carried out the measurements of static and dynamic surface tensions of the microcapsules containing casein hydrolysate within SPI and pectin for determination of sample adsorption at the air-water interface. Herein, three samples were prepared by varying the ratio of the wall material to the core. The concentration of the core material was varied as 50, 100, and 150%, keeping SPI and pectin ratio as 1:1 and the samples were named as M1, M2, and M3. Surface tension measurements were done using a drop tensiometer (TVT2 Lauda, Germany), which measured the contact angle of the drop using Laplace’s law. The results showed that surface tension of all the samples dropped initially and then remained constant, which is attributed to the behavior of the protein in the aqueous solution. At first, the proteins moved to the surface and unfolded, and then they rearranged to form multiple layers. Hence, the wall materials used did not act as effective surfactants. From the above study, it is clear that surface tension of the microcapsules is largely a function of the wall material used.

5.4.3 Hygroscopicity

Microcapsules when exposed to an environment with a high relative humidity, tend to absorb moisture from the environment and this property is called hygroscopicity. It decides the stability of the core material. Hygroscopicity of a microcapsule largely depends on the type of wall material which is used to hold the core material, that is, how hygroscopic it is. For example, for microencapsulation of oils and certain flavors, a wall material which is less hygroscopic is used, such as WPI. This property of the microcapsules during storage can be determined by using the sorption isotherms. Frascarelli et al. (2012) determined the critical storage conditions of the microencapsulated soybean lipids using the sorption isotherms of the microcapsules. The microcapsules were produced using spray drying technique and gum Arabic, WPI and mixtures of maltodextrin (MD) and WPI, at three different proportions (3:1, 1:1, and 1:3) were used as encapsulating agents. Sorption isotherms of the microcapsules were
determined by the gravimetric static method (Tonon et al., 2009). Results revealed that the microcapsules produced with gum arabic showed significantly higher water adsorption, while the microcapsules produced with WPI showed lowest hygroscopicity. Such property could be attributed to the different chemical structures of the wall materials used. Gum arabic has more number of ramifications with hydrophilic groups that can bind to water molecules easily, whereas whey protein has less number of such groups to interact with water, leading to lower hygroscopicity of the microcapsules. So, selection of wall material will significantly effect the hygroscopicity of the microcapsules obtained.

5.4.4 Encapsulation efficiency

Encapsulation efficiency is defined as the amount of core material that is encapsulated within a wall material, against the concentration of the core that was used for encapsulation, using a particular technique. It depends on the concentration of the core material that is used for encapsulation. With the increasing levels of the core material, encapsulation efficiency tends to decrease. In a study by Mendanha et al. (2009), encapsulation efficiency was determined by centrifuging the microcapsules and estimating the protein content (casein hydrolysate content) by using biureto-spectrophotometric method (Gornall et al., 1949). Formula for determining encapsulation efficiency is (Equation 1):

\[
EE\% = \frac{Total\ hydrolysate - Total\ free\ hydrolysate}{Total\ hydrolysate} \times 100
\]

Total free hydrolysate is the protein (g) in the supernatant, which does not take part in the formation of microcapsules. And total hydrolysate is the amount of protein (g) in the formulation. Another method of determining encapsulation efficiency of encapsulating certain oils, as mentioned by Bae and Lee (2008), involves use of solvents like hexane. Herein, the powder is mixed with a solvent like hexane for extracting the free oil, which is then filtered through a whatman no. 1 filter paper. Once the powder is obtained on the filter paper, it is washed numerous times with hexane and kept for drying at room temperature, then at 60 C for evaporating the solvent. Once a constant weight is obtained, the surface oil is determined by subtracting the weight of the initial clean glass container from that, which contains the extracted oil residue (Jafari et al., 2008). Similar methods were reported by Varavinits et al. (2001). And encapsulation efficiency is found out by Equation (2):

\[
EE = \frac{(TO - SO)}{TO} \times 100
\]

where EE is encapsulation efficiency, TO is total oil, and SO is surface oil. The dependence of encapsulation efficiency on the technique used for encapsulation as well as the matrices or coating materials can be observed from the results reported by Anwar & Kunz (2011), wherein the capsules formed with four different matrices combinations (MC), namely, MC-1, MC-2, MC-3, and MC-4 had different encapsulation efficiencies. And out of the three techniques, which were used for encapsulation, freeze drying showed lowest efficiency, followed by spray drying and spray granulation. Measurement of encapsulation efficiency is considered as the most crucial factor, as it only determines whether a particular functionality of the encapsulated component is being delivered into the food matrix or not.

5.4.5 Heat and light stability

In food products there are different compounds like vitamins, pigments, etc., which are very sensitive to the harsh processing conditions used in the food industry, like pasteurization, sterilization, baking, etc. These compounds need to be protected to prevent their degradation and, hence, losses in the foods. Thus, microencapsulation serves as one of the best techniques for the protection of such compounds. Sáiz-Abajo et al. (2013) used casein micelles to encapsulate β-carotene in order to protect it from degradation during various processing conditions. Casein micelles were subjected to heat treatments and it was found that the total β-carotene concentration in the microencapsulated samples slightly decreased during the initial period of the heat treatment, but remained constant from 4.5 to 8 h and a total decrease was only 30.9% as compared to control samples, where the decrease was observed continuously and the concentration decreased by 83.5% during the same period of time. Similarly, there are many other compounds which are light sensitive, thus, microencapsulation is used for enhancing the light stability of such compounds. Xue et al. (2013) prepared resveratrol dispersion in order to protect it from light and the light stability of the dispersion was determined by keeping the sample and the control (raw resveratrol) under Sun drying condition and then measuring the active ingredient by using UV spectrophotometer. Results showed that after 8 h of exposure to the sun light, concentration of raw resveratrol decreased to 20%, as compared to 57% drop in resveratrol dispersion. Thus, light stability was found to be improved by encapsulation.

6 DIFFERENT METHODS FOR CONTROLLED RELEASE OF THE CORE MATERIAL

Microencapsulation is considered to be effective only if the core material is protected until its release is desired. There are different mechanisms which are used for releasing the core material. These include degradation, diffusion, dissolution, application of pressure and change in temperature and pH. Mechanisms used are based on the properties of the core and the wall material.

Some of the methods are described below:

a. Diffusion:
Diffusion of the core normally occurs when the wall of the microcapsule is intact and a fluid penetrates through the wall, dissolves in it, the core material and disperses out through the pores.

b. Dissolution:
Here the release of the core depends upon the solubility of the wall material into the dissolution fluid. The wall remains no longer intact when comes in contact with the fluid, it solubilizes and releases the
core. The rate of release depends upon the properties of the wall material and dissolution fluid and the thickness of the wall.

c. Osmosis:
In osmotic release of the core material, the wall of the microcapsule behaves as a semipermeable membrane, which allows development of osmotic pressure difference on either side of the wall. Due to this pressure difference core material moves from inside of the capsule to outside.

d. Degradation:
In this method of core release, enzymes such as, proteases and lipases, are used to degrade the proteins and lipids in the wall material, hence breaking of the wall and releasing the core.

e. Change in pH:
Change in pH can lead to release of core as it can affect the solubility of the wall material. A wall material may be such that it remains intact under acidic conditions, while gets solubilized by altering the pH leading to alkaline conditions.

f. Changes in temperature:
Core release can be promoted by changing the temperature to which the microcapsules are exposed. For temperature-mediated core release, two different mechanisms are involved: (a) One is called temperature-sensitive release, where the wall material is such that it collapses when it gets exposed to a temperature known as the critical temperature, beyond which it cannot withstand and expands. (b) The other mechanism is called fusion-activated release, in which the wall material starts melting when it is exposed to an increased temperature and, hence, releases the core.

7 | DEGRADATION OF CORE IN THE MICROCAPSULES

To study the stability of the microcapsules under various conditions of temperature and pH and to determine how effective is the coating material and the encapsulation method in protecting the core during storage, degradation kinetic studies are performed for the microcapsules. While performing such studies, known amount of the microcapsules are stored under controlled conditions and taken out at regular intervals for determining the degradation in the core content. Table 5 shows comparison in degradation kinetics of various encapsulated compounds produced using different methods and coating materials.

8 | APPLICATION OF MICROENCAPSULATION WITH RESPECT TO FOOD INDUSTRIES

Microencapsulation has proven and is further considered to prove as an effective tool in creating novel food products with numerous functional properties, when looked from industrial point of view. Microencapsulation technology has been widely used in certain commercial food products like juices, chocolates, meat and poultry products, etc. Marcial-Coba, Saaby, Knøchel, and Nielsen (2018) reported the commercial availability of dark chocolates, which serve as a stable carrier of microencapsulated probiotic strains, namely, Akkermansia muciniphila and L. casei. These strains were encapsulated within xanthan gum matrix and then embedded in dark chocolate. Microencapsulated A. muciniphila showed better survival in the chocolate matrix under simulated gastric condition of pH 3, with an increase of 1.80 log CFU/mL and for L. casei, 0.8 logCFU/mL, when compared to the naked cells. Various other food products are also available commercially. Danone Research and Micopharma Inc. Canada have developed fermented milks with microencapsulated Lactobacillus reuteri incorporated in them. In Mexico, A company named Yoplait Inc. has commercialized a yoghurt containing encapsulated bifidobacteria, called “Bificapsulas.” Another company, Belgo & Bellas, Boisbriand, QC, Canada has marketed a product named, Yogactive®, which is a ready-to-eat cereal containing “pearls” of probiotic bacteria (Champagne & Kailasapathy, 2011). In bakery products, for production of short dough biscuits, vegetable shortenings are encapsulated and converted into oxidatively stable powders (O’Brien et al., 2003). In other food products also, like certain beverages, microcapsules of curcumin and catechin, prepared by water-in-oil-in-water emulsion are incorporated too serve as functional foods. Also, microencapsulation is used as an effective tool in transferring micronutrients into certain staples like rice and wheat for fortifying them. Microencapsulation technology has full potential to expand further in near future leading to the development of many more functional food products, thus, contributing to the growing food industry. However, production of microcapsules for applications in the food industries is very challenging, owing to many reasons like difficulty in scaling up of a process and dramatically increased production costs, which acts as a limitation in the economic viability of the process. Also, despite its immense scope to be used in food, complexity always prevails as food itself is a complex matrix. While encapsulating food ingredients, there are several limitations in choosing the wall materials, as they need to be food grade or generally recognized as safe (GRAS). When a core material is encapsulated, its interaction with the wall material, stability in various food matrices where it is used as an ingredient, during processing of food, needs to be properly understood. Another significant challenge is the release of core material at the appropriate site during digestion and it requires thorough understanding of the breakdown mechanisms of the food and encapsulated material inside the human digestive tract. And all these challenges need to be overcome without compromising the sensory qualities of the foods. So, careful consideration should be taken while choosing a coating material for encapsulation, the ratio of core to coating material, the method of encapsulation. Also, thorough evaluation of the properties of the microcapsules needs to be carried out before incorporation into any food matrix. Only then it will lead to successful implementation of the technology.

9 | CONCLUDING REMARKS

Different properties of the microcapsules and their method of determination have been discussed in this critical review. Effects of different techniques of microcapsule production, type of the core, and the
| Product         | Method          | Coating material                        | Results                                                                 | Inference                                                                                     | References          |
|-----------------|-----------------|------------------------------------------|--------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|----------------------|
| 1. Betanin      | Spray drying    | a. Maltodextrin                          | At pH 5, Degradation constant ($k \times 10^3$(d$^{-1}$)): 189.4 ± 6.9,  
At pH 6, degradation constant: 215.6 ± 6.3                 | Change in pH affected degradation of betanin, Xanthan gum increased the stability of betanin, freeze drying produced more stable microcapsules compared to spray drying | Antigo et al. (2018) |
|                 |                 | b. Maltodextrin & Xanthan gum            | At pH 5, degradation constant: 108.4 ± 1.6,  
At pH 6, Degradation constant: 118.8 ± 5.7                  |                                                                                               |                      |
| Freeze drying   |                 | a. Maltodextrin                          | At pH 5, Degradation constant: 110.6 ± 2.9,  
At pH 6, Degradation constant: 126.0 ± 4.0                 |                                                                                               |                      |
|                 |                 | b. Maltodextrin & Xanthan gum            | At pH 5, Degradation constant: 105.7 ± 4.0,  
At pH 6, Degradation constant: 101.4 ± 4.9                  |                                                                                               |                      |
| 2. Fucoxanthin  | Spray drying    | a. Maltodextrin                          | At temperature: 37°C, Degradation constant ($k \times 10^4 \pm s_k \times 10^2$(d$^{-1}$)): 0.61 ± 0.08 | Maltodextrin & Gum Arabic better protected fucoxanthin than Whey Protein Isolate | Sun et al. (2018)    |
|                 |                 | (b) Gum Arabic                           | At Temperature: 37°C Degradation constant: 0.76 ± 0.03                  |                                                                                               |                      |
|                 |                 | (c) Whey Protein Isolate                 | At Temperature: 37°C Degradation constant: 1.240.94                    |                                                                                               |                      |
| 3. Anthocyanin  | Spray drying    | a. Maltodextrin                          | At 4°C, degradation constant ($k \times 10^3 \pm s_k \times 10^2$(d$^{-1}$)): 4.2 ± 0.3,  
At 25°C, degradation constant: 4.4 ± 0.3  
At 37°C, degradation constant: 4.6 ± 0.3                 | With the increase in temperature, degradation of anthocyanin increased, Combination of maltodextrin and gum arabic better protected anthocyanin from degradation | Idham et al. (2012)  |
|                 |                 | b. Gum arabic                            | At 4°C, degradation constant: 4.9 ± 0.2,  
At 25°C, degradation constant: 4.9 ± 0.3  
At 37°C, degradation constant: 5.3 ± 0.6                 |                                                                                               |                      |
|                 |                 | (c) Maltodextrin + Gum arabic            | At 4°C, degradation constant: 3.7 ± 0.3,  
At 25°C, degradation constant: 4.3 ± 0.3  
At 37°C, degradation constant: 4.6 ± 0.2                 |                                                                                               |                      |
|                 |                 | d. Soluble starch                        | At 4°C, degradation constant: 5.7 ± 0.4,  
At 25°C, degradation constant: 5.7 ± 0.7  
At 37°C, degradation constant: 6.7 ± 0.6                 |                                                                                               |                      |

Wall material and the storage conditions were also discussed. After critically analyzing the important properties of the capsules, it can be said that the physical properties of the microcapsules like porosity, hydrophobicity, and flow behavior are important to determine their storage state and their packaging mode, micromechanical properties are used to determine the best possible way for controlled release of the core material, thermal properties decide the storage stability of the capsules, and the functional properties like solubility, surface tension, and hygroscopicity are important to study the behavior of the capsules in any food matrix. And thus, it can be concluded that the properties...
of the microcapsules differ according to the different techniques used, type of core material, and the type of shell material used and on the basis of these properties only, packaging and storage conditions are decided. Also, based on these properties only, the microcapsules can be transferred to respective food matrices, hence, serving as a mode for developing functional foods.

CONFLICT OF INTERESTS

The authors declare no conflict of interest.

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