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A review on encapsulation of food bioactive compounds and their controlled release mechanisms

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Abstract
Functional foods are supplemented with functional ingredients and active constituents to provide health benefits and avoid diseases. The incorporation of bioactive constituents is quite sensitive and their function in the food is a major challenge for the food industries. Encapsulation is considered as an advanced food processing technique used for encapsulation of bioactive materials and protecting them against environmental conditions. Encapsulation 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. The selection of core and wall materials for encapsulation needs to be worked carefully to have good stability and shelf life of functional food products. The selection of the right release mechanism is important for delivering compounds. Controlled release is an important platform for formulation and improves the performance of food ingredients in food products and the human body. The controlled release provides optimal release and increases the overall performance and stability of encapsulation. The encapsulated products have wide applications in food industries for shelf life stability and quality improvement of food products.

Keywords: Bioactive compounds, control release, encapsulation, functional food, mechanisms

1. Introduction

With changing lifestyles, there has been a surge in demand for healthy and nutritional food products worldwide. Consuming food that not only satisfies hunger but also provides essential nutrients is crucial for humans. People require food, that prevent them from diseases and enhance their physical and mental health (Sharma *et al.*, 2021) [29]. With this demand from consumers, functional foods defined an outstanding role in the health of humans. Functional foods are supplemented with functional ingredients and active constituents to provide health benefits and avoid chronic diseases. The incorporation of bioactive constituents in food is a major challenge for the food industry due to their delicate nature and sensitive functionality. The bioactive compounds present in food are active compounds that provide health status (Yousuf *et al.*, 2016) [33]. These active components include lipids, proteins, minerals, vitamins, antioxidants and probiotic bacteria. To protect the food ingredients from severe processing conditions and to continue strengthening their bioactivity and bio functionality, the development of functional and nutritional food with active ingredients has been intended with the novel food-related colloidal delivery systems (Rostamabadi *et al.*, 2021) [27]. The bulk of bioactive substances are lipophilic and have a limited solubility in water, which makes it challenging to incorporate them into most diets. Additionally, absorption in the gastrointestinal tract is reduced because of the poor solubility. The production of functional meals required the use of an edible delivery system for the encapsulation, protection, and release of active chemicals (Marcillo-Parra *et al.*, 2021) [17]. The microencapsulation and nanoencapsulation techniques are appropriate for engineered designs and the manufacture of colloidal delivery systems to deliver bioactive compounds. The encapsulation process causes the core material to be embedded in the wall material for the proper control release at a specific time. Encapsulation is regarded as the best technique for the food industries as it provides preservation of components and additives instead of their direct incorporation in a food system (Machtakova *et al.*, 2022) [16]. The utilization of this technology is to protect the sensitive bioactive constituents and for the fabrication of novel food formulations with better characteristics. Encapsulation aids to enhance the stability and bioavailability of bioactive components, and also regarded as one of the most often used alternatives to traditional food processing (Ghosh *et al.*, 2022) [10]. As encapsulated goods have such great health advantages, they can be used as functional food additives. The encapsulation approach improves the dispersibility of active substances in an aqueous solution, decreases the propensity for the liquid and lipid phases to separate, protects the active substances, shields their functional qualities, and prevents food deterioration (Marcillo-Parra *et al*., 2021; Rostamabadi *et al*., 2021) [17, 27].

The encapsulation process protected the bioactive components from the unfavorable food processing conditions. Further, this approach also minimizes the impact of organoleptic characteristics of food, enhance absorption and bioavailability, and improves the passive transport mechanisms across the cell membrane. This approach has usage in the industries of medicines and nutraceutics (Rostamabadi *et al*., 2021) [27]. The presence of the active compounds and human biological activity lead to their usage as natural additives in the pharmaceutical, biotechnology, and food industries. The factors including temperature, pH, light, oxygen, and ions are all unstable when food is under processing and in stored conditions (Peanparkdee and Iwamoto, 2022) [22]. The process of encapsulation proved to be useful for bioactive chemicals and reduced environmental sensitivity while boosting their stability and water solubility. The functional chemicals can be delivered to the target site under regulated conditions, due to the advancements in the techniques of encapsulation with enhanced bioavailability, water solubility, and stability (Peanparkdee and Iwamoto, 2022; Ghosh *et al*., 2021) [22]. The present review discuss the encapsulation of various food bioactives; and their control release mechanisms.

2. Encapsulation of different bioactive compounds

The encapsulation of different bioactive compounds provides enhanced and improved quality and shelf life of food products. Different components that can be encapsulated are lipids, vitamins and minerals, flavors, enzymes, essential oils etc. Table 1. identified the encapsulation of bioactive constituents and their encapsulation system. The encapsulation of different bioactive components are discussed below:

2.1 Encapsulation of Lipids

Lipids are mainly waxy, fatty and oily compounds that are easily dissolve in organic solvents and are not dissolvable in polar solvents such as water. Different materials utilized for encapsulation of lipids are carrageenans, alginates, chitosan, xanthan, dextran, gellan. etc. For encapsulation of lipids with different materials different methods are utilized. These methods including liposome encapsulation, coacervation and co-extrusion and centrifugal extrusion. Nanoemulsions are crucial for encapsulation matrices to safeguard bioactive namely lipids. The bioactive such as lipids defined low odor thresholds and had an impact on sensory matrics at extremely low concentrations. Nanoemulsion aqueous phase are utilized to stabilize lipids shields against stressors that cause its chemical degradation (Popovi *et al*., 2019) [23]. Controlled material release is possible by adjusting the components' characteristics in nanoemulsions as well as factors like time, temperature, pH, and ionic concentration. The advantages of employing nanoemulsion-based encapsulation for lipids include reduced autoxidation, improved functional characteristics, solubilization of tastes and volatile chemicals, masked bitter taste and protection of active molecules in the gastrointestinal tract (Mourtzinos *et al*., 2017) [19].

2.2 Encapsulation of vitamins and minerals

Vitamins and minerals are micronutrients vital by the body to perform normal functions. These nutrients are not produced by our body and are carried from the food that we consume. Different materials used for encapsulation of minerals are chitosan, gums, pectin, maltodextrin, starch, whey, cellulose, sodium alginate, protein, sodium caseinate, galactomannan. etc. The methods used for encapsulation of vitamins and minerals are spray drying, spray cooling, fluidized bed coating, coacervation. etc. The coacervation method used to encapsulate vitamin A. The fat-soluble vitamins (A, D, E, K) and water-soluble vitamins (B, C) can be encapsulated by using the wall material such as tripolyphosphate, cross-linked chitosan, starch, β-cyclodextrin, malto dextrin, gum arabic etc. It helped to preserve the nutritional value, taste, shelf life and bioavailability of bioactive ingredients (Dias *et al*., 2017) [11]. As iron is considered an important element for the human body and inadequate consumption causes the deficiency of iron in the body. One of the ways to avoid this issue is to fortify the food with iron. The iron catalyzes oxidative processes in vitamins, fatty acids and amino acids causing a loss of sensory and nutritional value of the food. Encapsulation process prevents these reactions. Different encapsulation processes such as spray drying, fluidised bed coating, extrusion, molecular inclusion and coacervation are utilized to encapsulate the vitamins and minerals (Dias *et al*., 2017; Chew *et al*., 2019) [11, 5].

2.3 Encapsulation of Flavors

A flavoring agent is also called as flavor used as a food additive that further utilized to enhance the taste or smell of food. The materials including alginates, gellan gum, glucuronic acid, carrageenan, hexuronic acids are utilized for encapsulation of flavors. Techniques that favored the flavors for encapsulation are coacervation, liposome encapsulation, molecular encapsulation, co-extrusion and centrifugal extrusion. Flavors have an important role in consumer satisfaction and have a great influence on food consumption. Flavor's long residual action and less thermostability are two factors which prevent the flavour business from developing further. The encapsulation process is important for increasing the stability of tastes. Sometimes, specific flavors and fragrances are affected by the encapsulation process which results in unpleasant tastes and odours (Niu *et al*., 2020; Mourtzinos *et al*., 2017) [21, 19]. Different variables including material characteristics, formulation, and operation circumstances affect the encapsulation of the flavors. The rate at which the active chemicals are released depends on the final characteristics of the particles. For the encapsulation of bioactive constituents namely flavours in the food industry, various issues including manufacturing, storage qualities, consumer satisfaction, and economic viability are important. The complex cooking is regarded as chemical process utilized for preserving the flavor molecules (Niu *et al*., 2020) [21].

2.4 Encapsulation of Enzymes

Enzymes are complex proteins, or biomacromolecules, with particular catalytic enzyme functions. The enzymes control the necessary chemical processes for human metabolism. Mainly agar-agar and agarose gels are used for encapsulation of enzymes. The methods such as covalent attachment, bio-conjugation, physical entrapment, non-covalent adsorption and deposition are utilized for enzymes encapsulation. It has been seen that enzyme's catalytic capability in aqueous solution under normal pressure and temperature creates significant economic and industrial value (Peanparkdee and Iwamoto, 2022; Chew *et al*., 2019) [22, 5]. The semi-permeable membrane is used in the encapsulation approach to capture the enzymes, preventing any disruption of the enzyme activity. The big size molecules such as starch and proteins are utilized in encapsulation of enzymes and the movement of the substrate to the active sites is restricted by diffusional limits, which could damage the kinetics of the enzymes (Niu *et al*., 2020) [21].

2.5 Encapsulation of essential oils

Essential oils are lipid-based, volatile, aromatic substances that are extracted from the entire plant as well as from various parts of the plant, including the flowers, seeds, buds, leaves, bark, resins, and roots. Essential oils might potentially improve health and are effective at preserving food. Agar, alginate, proteins, dextrins, Arabic gum are some materials used for encapsulation of essential oils. The methods such as spray drying and coacervation are utilized for essential oils encpasualtion. The hydrophobic volatile essential oils are immediately constrained in terms of food integration (Marcillo-Parra *et al*., 2021; Rostamabadi *et al*., 2021) [17, 27]. Essential oils can be added to nanoemulsions to help with the difficulty of incorporating them into food. When making oil-based emulsions, high-energy techniques are used to first pre-dissolve the essential oils in the oil phase before emulsifying them in the aqueous phase (Rostamabadi *et al*., 2021). The creation of essential oil nanoemulsions through homogenization defined enhanced antibacterial and antioxidant capabilities. The continuous phase of the oil-in-water emulsion is provided with prolonged release of the antimicrobials by including antimicrobial compounds at a concentration greater than their water solubility. One approach for creating successful essential oil nanoemulsions is the spontaneous emulsification method. This is a low energy method, with which nanoemulsions can be forned by magnetic stirring the components. (Peanparkdee and Iwamoto, 2022) [22].

Table 1: Different bioactive constituents and their encapsulation system

Bioactive class	Compounds or Matrix	Technique	Particle size (nm)	Factors affecting active compounds	Applications	References
Lipids	Plant essential oils (Clove, Oregano) + Methylcellulose	Ultrasonication + Spray drying	180–250	• Oxidation • Solubility • Viscosity • pH	• Increased bioavailability • Preservative effect • Sustained release • Rigidity and increased the extensibility	Rostamabadi *et al*., 2021 [27]
	Fish oil, Lemon oil + Maltodextrin	Emulsification process	>100	• Oil composition • Surfactant mixture • Oxidation • Solubility	• Stability • Systematic bioavailability	Peanparkdee and Iwamoto, 2022 [22]
	β-lactoglobulin + lactoferrin	Homogenization + Spray drying	45	• Rheological behaviour • Solubility • Oxidation • Viscosity	• Improves sensory quality of products • Water and fat rich functional foods	Marcillo-Parra *et al*., 2021 [17]
Vitamins	Vitamin E + Mustard oil	Emulsification process	86.45 ± 3.61	• Rheological behaviour • Solubility • Oxidation • Viscosity • pH	• Crucial for growth and development of body • Antioxidants • Antimicrobial activity • Improves stability • Increased shelf life	Dasgupta *et al*., 2016 [7]
	Vitamin E-acetate + Whey protein isolate (WPI) and Gum arabic (GA)	Emulsification process + Spray drying	>100	• Isoelectric point • Ionic strength • Solubility	• Produce stable nanoemulsions • Produced smaller droplets • Enriched delivery	Niu *et al*., 2020 [21]
	Vitamin E + Whey protein isolate (WPI)	Emulsification process	50	• Turbidity • Isoelectric point • Ionic strength • Solubility	• Thermal stability • Antimicrobial activity • Improves stability • Increased shelf life	Marcillo-Parra *et al*., 2021 [17]
	Folic acid + Whey protein, resistant starch	Nano-spray drying/electrospraying	>100	• Turbidity • Isoelectric point • Ionic strength	• Higher encapsulation efficacy • Improved acid stability	Rostamabadi *et al*., 2021 [27]

	Vitamin E + Octenyl Succinic Anhydride (OSA) modified starch	Spray drying	>100	• Solubility • Viscosity • pH	• Retention and storage stability • Improved emulsification capacity	Peanparkdee and Iwamoto, 2022 [22]
	Vitamin C, E + Liposomes	Liposomal encapsulation	100	• Solubility • Viscosity • pH	• Oxidative stability • Retention and storage stability • Improved emulsification capacity	Marcillo-Parra *et al.*, 2021 [17]
Antioxidants	Ascorbic acid, Tocopherol + Carotenes	Emulsion-encapsulation	50	• Isoelectric point • Ionic strength • Solubility	• Retard degradation • Improves efficiency • Controlled release • Improve stability and bioavailability of polyphenols	Lu *et al.*, 2016 [15]
	β-carotene + Orange oil	Emulsion-encapsulation	< 200	• Solubility • Viscosity • Turbidity • Absorption rate	• Improves efficiency • Controlled release • Improve stability and bioavailability of polyphenols	Niu *et al.*, 2020 [21]
Antimicrobials	Essential oils (eugenol, carvacrol) + Bioactive peptides (nisin, casecidins, lactoferricin-f)	Emulsion-encapsulation	>100	• Solubility • Viscosity • Turbidity • Absorption rate	• Reduce the risk of chronic diseases • Health-enhancing nutraceuticals	Mohanty *et al.*, 2016 [18]
	Resveratrol + Grapeseed oil, Orange oil	Spontaneous emulsification	≈ 100	• Rheological behaviour • Solubility • Viscosity	• Avoid degradation • Thermal stability • Antioxidant • Antimicrobial	Davidov-Pardo and McClements, 2015 [8]
	Trans-cinnamaldehyde + Phenolic compounds	Emulsification process + Spray drying	<200	• Temperature • pH • Solubility • Viscosity • Water absorption	• Maintained encapsulation efficiency • Antioxidant • Antimicrobial	Jo *et al.*, 2015 [13]
Flavors	Lactoferrin + calcium alginate	Emulsification process	<100	• Temperature • pH • Solubility • Water absorption • Rheological behaviour	• Maintained encapsulation efficiency • Thermal stability • Antioxidant • Antimicrobial	Raei *et al.*, 2015 [25]
	Thiol + Protein	Spray drying	>100	• Temperature • pH • Solubility • Viscosity • Water activity	• Improves efficiency • Controlled release • Improve stability and bioavailability	Marcillo-Parra *et al.*, 2021 [17]
Enzymes	Roasted coffee oil + Lipids	Miniemulsion/solvent evaporation	>100	• Solubility • Viscosity • Water activity • Temperature	• Retard biochemical degradation • Increase effectiveness	Lu *et al.*, 2016 [15]
	Cellulases and Hemicellulases + alginate	Spray drying	>100	• Solubility • Viscosity • Temperature	• Improve stability • Controlled delivery • Control the release	Amjadi *et al.*, 2018 [1]
Natural colorants	Saffron + maltodextrin, gum Arabic, gelatin	Spray drying	<100	• Solubility • Viscosity • Temperature	• Improve stability • Increase effectiveness	de Matos *et al.*, 2018 [9]
	Betanin + Liposomes	Liposomal encapsulation	>100	• Rheological behaviour • Solubility • Viscosity • pH	• Increase the bioavailability • Antioxidant • Antimicrobial	Amjadi *et al.*, 2018 [1]
Essential oils	Rosemary essential oil + whey protein concentrate (WP), Maltodextrin	Freeze drying	>100	• Rheological behaviour • Solubility	• Increase the bioavailability • Antioxidant	Raei *et al.*, 2015 [25]

				• Viscosity • pH	• Antimicrobial • Improves the stability	
	Citronella essential oil + gelatin, sodium alginate	Complex coacervation	-	• Solubility • Viscosity • Turbidity • Absorption rate	• Maintained encapsulation efficiency • Thermal stability • Antioxidant • Antimicrobial	de Matos *et al.*, 2018 [9]
	Linseed oil + quercetin	Solid liposomal encapsulation	>100	• Solubility • Viscosity • Turbidity	• Maintained encapsulation efficiency • Thermal stability • Antioxidant • Antimicrobial	Huang *et al.*, 2020 [12]

3. Control release of the encapsulated bioactive compounds and its mechanism

Controlled release is one type of modified release system to have a specific concentration of the target site conditions. It means the release of bioactive components at the target place over a specified period of time. Control release is also effective in the bioavailability and bioaccessibility of encapsulated bioactive components (Sivasankaran and Jonnalagadda, 2021) [30]. It is the process by which one or more active agents appear at the target point at a desired rate and time. Control release is primarily used to reduce the loss of target chemicals, such as vitamins and minerals during processing and storage, as well as to maximize absorption and improve effective use. The primary benefit of controlled release is the gradual release of active substances over time at predetermined rates (Rezaei *et al*., 2022) [26]. The methods utilized are thermal and moisture release. The major factors involved are temperature, pH, solvent, diffusion, swelling, degradation, osmotic pressure (Yang *et al*., 2022) [32]. Figure 1. described different release mechanism for encapsulated food components. The control release mechanism involves different release mechanism and their functions. Some release mechanisms are discussed below:

3.1 Diffusion

The diffusion method is considered one of the most significant methods for control release. Bioactive molecules move randomly under the influence of a potential chemical gradient and are made available by a concentration gradient (Augustine *et al*., 2021) [2]. It takes place from the carriers' interior to exterior and involves rate-limiting locations during release events. It is due to the bioactive's permeability and solvability. The diffusion occurs lowest in the solid form and fastest in the gaseous one. The encapsulation system is stable during the throughout release mechanism of diffusion and further, it may alter to erosion, swelling, dissolution, shrinkage, fragmentation events (Navrátil *et al*., 2022) [20].

3.2 Dissolution

The bioactive components would release into the surrounding areas when the carrier components were present in a specific setting, such as those with appropriate thermodynamics. Dissolution starts outside of the carrier system and continues until it becomes easy to create. Two categories exist for the breakdown of the releasing mechanism. The first one is the encapsulation dissolution control release system, where the food contents are contained within the slowly dissolving compounds (Comunian *et al*., 2022) [6]. The solubility profile of the food ingredients and the carrier's inherent characteristics both affect how quickly the substance dissolves in this. The second method uses a matrix-dissolution control release system, in which the bioactive substances are evenly distributed across the particle's surface. The solvent is involved in both the erosion and swelling processes and increases the diffusion rate, making the dissolving mechanism more difficult to understand than the diffusion mechanism (Navrátil *et al*., 2022; Augustine *et al*., 2021) [20, 2].

3.3 Erosion

There are two groups of erosion-controlled means. The first type of degradation is surface erosion, which solely affects the carrier's exterior. The second is bulk erosion, in which the carrier's entire surface degrades. The release mechanism is characterized as the erosion mechanism with no transport of components. In this, erosion as well as the mass loss of the polymer happened as a result of the polymers' degradation and products diffusing into the release environment (Cai *et al*., 2022; Sivasankaran and Jonnalagadda, 2021) [4, 30]. Based on the erosion rate at the location of occurrence, which is affected by the carrier and the environment, the release mechanism is managed. The pores created by the erosion mechanism speed up the diffusion process. Releases are regarded as erosion-controlled when diffusion surpasses erosion (Rezaei *et al*., 2022) [26].

3.4 Swelling

When release happened because of the solvent's absorption, the encapsulation was thought to have swollen. The rate of release in this case depends on the rate of swelling as well as how long it takes for the meal elements to be distributed throughout the swollen system (Saifullah *et al*., 2019) [28]. The nutrients or other elements that function as osmolytes in the polymeric systems and induce solvent diffusion into the carrier are the key manipulators of these systems. By choosing the proper polymeric matrix and managing external factors like pH and temperature, it is possible to control the swelling release mechanism (Boostani and Jafari, 2021) [3].

3.5 Osmosis

Osmotic pressure is required for the infiltration of water into a non-swelling system in order to improve osmotic pumping and bioactive transport. This transport's nature is more closely linked to convection than to diffusion (Li *et al*., 2021) [14]. This occurs when a highly selective water permeable carrier with small orifices that is stable against the encapsulated compounds meets an aqueous medium, and water absorption occurs to create the osmotic pressure and release (Boostani and Jafari, 2021) [3]. The osmosis release process resembles the swelling release mechanism in which the carrier system absorbs the solvent over time and creates swelling that lasts until it is destroyed. Cracks form in the coating materials, the carrier swells, and the coating is destroyed (Trojer *et al*., 2013) [31].

3.6 Degradation
In this method, the combined chemicals are dispersed throughout the carrier and released by eroding or decomposing a polymer system. It entails a process of chain scission or breakdown involving biological systems or microbes. Early autocatalysis processes cause the biodegradable chemicals to break down gradually, but over time the rate of deterioration accelerates or erodes (Premjit *et al*., 2022) [24]. In hydrophilic polymers, homogeneous erosion is most frequently utilized, whereas heterogeneous erosion is more frequently used in hydrophobic polymers. Due to its continual release outside on the encapsulated compounds, the heterogeneous compounds are mostly utilized for controlled release (Zaitoon and Lim, 2022) [34].

3.7 Fragmentation
Food ingredients are mostly released through the fragmentation mechanism when there is a breakdown or crack in the carrier material as a result of environmental factors like shearing events, pressure, pH and enzymatic activity. The fracture characteristics of the encapsulating system, such as applied stress at the breakpoint, control the rate of release (Li *et al*., 2021; Trojer *et al*., 2013) [14, 31]. The release rate has an impact on the pieces' size and shape as well. Diffusion, erosion, dissolution, and degradation are the main release mechanisms used to liberate the bioactive from the fragments. Faster release rates result from the production of smaller particles and an increase in surface area (Boostani and Jafari, 2021) [3].

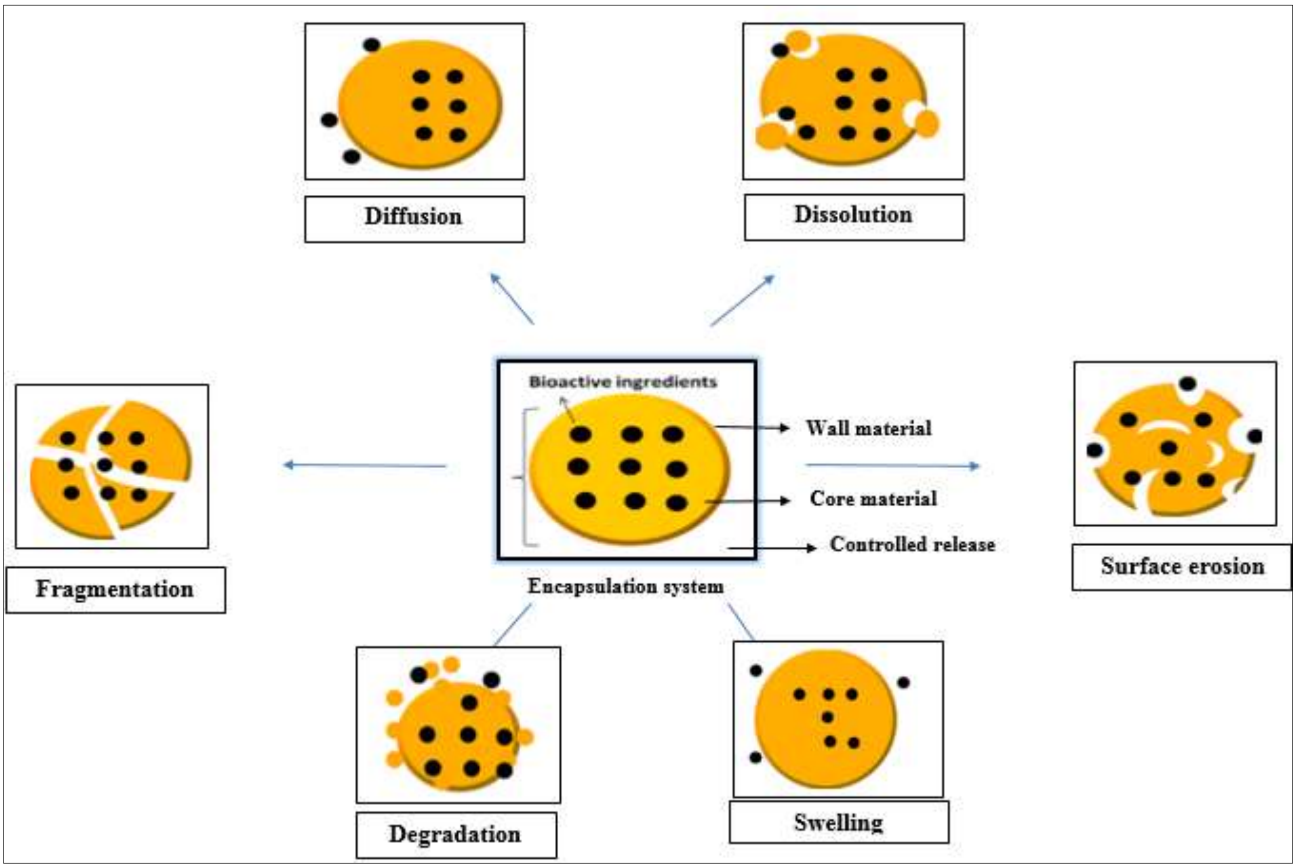

Fig 2: Different release mechanism for encapsulated food components (adapted from Boostani ans Jafari *et al*., 2021) [3]

4. Conclusion
The encapsulation process is an effective way to preserve active agents against evaporation, stress, oxidation and migration of foods. It is used to create premium functional food components with improved physical and functional qualities. The selection of coating material and encapsulating technique is crucial for having the optimal encapsulation. The encapsulation technique has numerous uses in the pharmaceutical and food sectors. Having original, healthy food products that can be advanced by a multidisciplinary research strategy and industrial needs is seen as an innovative instrument for the food sector. Encapsulation is the best way to improve the shelf life stability and quality of food products. Apart from this they are good at the controlled release of components and developing functional foods. The release mechanism is helpful in the safe delivery of bioactive components and in avoiding the degradation of components. Consumer interest in this technology is growing as a result of its possible applications and the delivery of active substances linked to improved consciousness and health advantages. As with the current demand from industries and consumers the development of ready-to-eat food products is improved by the encapsulation technique and enhances the nutritional value and functional properties by the introduction of different bioactive constituents.

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