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Gıda Teknolojisinde Enkapsülasyon Uygulamaları ve Güncel Çalışmalar

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Öne Çıkanlar:
- Enkapsülasyon metodunun gıda teknolojisinde geniş bir kullanım yelpazesi vardır

Anahtar Kelimeler:
- Gıda
- Enkapsülasyon
- Kontrollü salınım

ÖZET:

Enkapsülasyon gıda bileşen, hücre, enzim ve farklı maddelerin, protein veya karbonhidrat bazlı mini kapsüller içinde tutulup kontrollü salınımı ve stabilitesini sağlayan bir yöntemdir. Bir başka deyişle kullanılacak aktif materyalin nano, mikro veya milimetrik ölçülerde kaplama malzemeleri içinde tutulması olarak da tanımlanabilir. Enkapsülasyon metodunun gıda endüstrisi için büyük bir potansiyeli vardır. Bu yöntemde istenmeyen tat ve aroma bileşenlerinin maskelenmesi, kullanılan biyoaktif bileşiklerin dış etkenlerden korunması, bu bileşenlerin fonksiyonelliğinden yararlanımın arttırılması ve raf ömrü boyunca kontrollü salınımı hedeflenir. Değerli bazı gıda bileşenleri, esansiyel yağlar, lipitler, aromatik hidrokarbonlar, vitaminler, tatlandırıcılar, enzimler, renklendiriciler, mikroorganizmalar ve mikrobiyal metabolitler gibi çeşitli bileşenler farklı yöntemler kullanılarak enkapsüle edilebilmektedir. Bu derlemede, yöntemi anlamak için gerekli olan enkapsülasyon prosesleri, kaplama materyalleri, gıda teknolojisindeki uygulama alanları ve alanda yapılmış güncel çalışmalar araştırılmıştır. Derlemede, enkapsülasyon teknolojisi için genel bilgiler verilmekte olup yapılacak yeni çalışmalar için kısa bir literatür özeti olması hedeflenmiştir.

Encapsulation Applications and Current Studies in Food Technology

Highlights:
- The encapsulation method has a wide range of uses in food technology

Keywords:
- Food
- Encapsulation
- Controlled release

ABSTRACT:

Encapsulation, as a method that provides controlled release and stability of food components, cells, enzymes and different substances in protein or carbohydrate-based mini capsules. In other words, it can also be defined as keeping the active material to be used in nano, micro or millimeter sized coating materials. The encapsulation method has great importance and potential for the food industry. In this method, it is aimed to mask undesirable taste and aroma components, to protect the bioactive compounds used from external factors, to increase the utilization of their functionality, and to control their release during shelf life. Various components such as some valuable food components, essential oils, lipids, aromatic hydrocarbons, vitamins, flavourings, enzymes, colourants, microorganisms, and microbial metabolites can be encapsulated using different methods. In this review, the encapsulation process types, coating materials, application areas in food technology and current studies in the field were investigated in order to understand the method. In the review, general information is given for encapsulation technology and a brief literature summary is intended for new studies to be conducted.

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INTRODUCTION

Encapsulation can be defined as the process of enclosing liquid, solid, or gas food components, cells, enzymes, and other materials within carbohydrate or protein-based miniature capsules. In this method, cells are trapped in semi-permeable membrane, also known as capsule or coating agents (Dubey et al., 2009; Ünal and Erginkaya, 2010).

Encapsulation is used in various field, including pharmaceutical, agriculture, medicine, cosmetics, chemistry, and the food industry. In recent years, its importance has grown, especially due to the rising significance of functional foods in the food industry (Koç et al., 2010).

In the food industry, encapsulation technology is applied to fats and oils, colorants, aroma ingredients, microorganisms, minerals, vitamins, and enzymes. The primary goal of this method is to enhance the resistance of these meterials to environmental conditions through coating (Fang and Bhandari, 2010)

Encapsulation technology offers several advantages, including the preservation of functional properties by reducing material degradation during storage, protection of the substance from external factors, prevention of undesirable taste and odor changes, controlled release, ease of transportation and packaging, and an increased shelf life (Koç et al., 2010; Kanat and Gülel, 2021).

Encapsulation involves two distinct components: the active ingredient and the coating substance (Cavalheiro et al., 2015; Anandharamakrishnan and Parthasarathi, 2019). Capsules can be classified by size into macrocapsules (>5.000 µm), microcapsules (0.2 to 5.000 µm), and nanocapsules (<0.2 µm) according to their size (Gökmen et al., 2012).

In the food industry, various polysaccharides, proteins and lipids are commonly used as coating agents. Examples of polysaccharides include starch and its derivatives, cellulose and its derivatives, chitosan, and gellan. Proteins used as coating agents include whey proteins, casein, gelatin and gluten. Lipids used include fatty acids and alcohols, glycerides, phospholipids and waxes (Nedovic et al., 2011).

In encapsulation technology, the choice of coating material is crucial, but the coating method is also varied. There are both physical or chemical coating methods available. Physical methods include spray drying, spray cooling, lyophilization, molecular encapsulation, emulsion, air suspension coating, rotary suspension coating and extrusion. Chemical methods include coacervation and liposome encapsulation (Azab et al., 2019; Ibrahim et al., 2020).

This study explores, microencapsulation technology, including the various coating materials and methods that can be used, as well as their applications and potential in food technology.

Coating Material and Methods

The first step in encapsulation processes is the selection of a suitable coating material. Coatings are generally film-forming substances such as sugars, proteins, gums, natural or modified polysaccharides, oils and synthetic polymers (Dubey et al., 2009; Ünal and Erginkaya, 2010). Polysaccharides such as alginate, starch, cellulose, pectin, chitosan, and carrageenan; lipids such as hydrogenated vegetable oils; proteins such as casein, gelatin, whey, β-lactoglobulin and soya are the most commonly used coating materials (Martín et al., 2015). Polysaccharides, lipids and proteins are commonly used coating materials in encapsulation process. Alginate, starch, cellulose, pectin, chitosan and carrageenans are polysaccharides; hydrogenated and vegetable oils as lipids; casein, gelatin, whey, β-lactoglobulin and soya are examples of proteins (Martín et al., 2015). These polymeric coatings are used to isolate the core, protect the film layer and dissolve with a special stimulus at the ideal place or time, allowing the core to be released. The ideal wall material should not react with the core, protect the core in the capsule against adverse conditions at the maximum level, be economical and not spoil the taste of the food (Nazzaro et al., 2012).

There are various encapsulation methods, both physical, such as spray drying and cooling, lyophilization, molecular arrest and emulsion, air suspension coating, rotary suspension coating, extrusion and chemical, such as coacervation and liposome formation. When selecting the appropriate method, consideration must be given to factors such as the physical and chemical properties. Considerations include the process to be applied, the structure of the active substance, the desired particle size, the release mechanism, production scale and associated costs (Atak et al., 2017).

Spray dryer and cooler method

Spray drying is a method based on the principle that the shell material is dissolved in a polymer solution and then sprayed in aerosol form into a cabinet with hot air via an atomizer. The solvent is removed with the aid of hot air and the increased surface area from the spraying process allows for rapid drying within a short time frame of 3 to 40 seconds, resulting in the formation of microcapsules (Drusch, 2007). This method is the most commonly used due to the advantages such as having large and simple equipment, the ability to use a wide variety of coating materials, high efficiency and low cost. On the other hand, during the encapsulation by spray cooling, the core material and the coating material are fed into the cold air environment. It is especially used for coating active materials sensitive to heat and water. Due to the low working temperature, the coating material solidifies without evaporation around the material intended to be coated. It is similar to the spray dryer method. The difference between them is that drying is done not with hot air, but with cooling (Topbaş, 2011).

Extrusion (hot melt) method

In the extrusion method, a mixture of core material and molten carbohydrate matrix is prepared. The mixture passes through the extrusion nozzle via a series of moulds and is rapidly encapsulated in a solidification bath (Whelehan and Marison 2011; Heidebach et al., 2012). In this method, components such as alginate, whey proteins, starch, pectin are generally used as coating materials. Nevertheless, it can be said that alginate is the most suitable component for this technique (Geniş and Tuncer, 2019). The extrusion method is generally used in the food sector for the encapsulation of volatile and less stable flavouring substances and bacteria for reasons such as increased stability in bacterial viability. The method has advantages such as easy application, low cost, high bacterial viability (Nami et al., 2020). The most significant disadvantage of this method is the difficulty of application in large-scale production due to the slow formation of capsules (Burgain et al., 2011).

Lyophilization

Freeze-drying is a technique of encapsulation generally applied for the preservation of heat-sensitive biological substance such as flavors, proteins and living microorganisms. The freeze-drying method involves freezing the liquid in the material and lyophilization (water removal) under vacuum while it is frozen (Sobel et al., 2014). Advantages of the freeze-drying method include low aroma loss, good reconstitution properties of the produced product and minimal losses due to the movement of solutes in the food (Geankoplis et al., 2018). However, the method’s disadvantages include relatively high cost and prolonged processing time (Araújo et al., 2020).

Air suspension and rotary suspension (rotating disc)coating method

This method is based on suspending the core in an air stream that is heated or cooled by upward movement. After the dissolved coating materials in a molten or evaporable solvent are atomized into the cell by means of a nozzle, a very thin boundary layer is formed on the surface of the suspended particles. The suspended particles move outwards when the air flow reaches its highest point and then reach the fluidized bed dryer with the downward air column, where the coating material dries and hardens. In the system, cold air is used for solvent-based coatings and hot air is used for volatile components (Desai and Jin Park, 2005).

Rotary disc coating method as a relatively new technique, the inner material is introduced to the rotating disc in a homogeneously dissolved state in the membrane. As a result of the cooling and solidification of the membrane material, microcapsule formation is achieved by trapping the inner material (Paulo and Santos, 2017).

Complex creation method

Cyclodextrins, a cyclic derivative of starch, are used in this method, also called molecular trapping or inclusion. As cyclodextrins, α, β, γ-cyclodextrins are oligosaccharides consisting of 6, 7 and 8 glucose units, respectively, and bonded by α-1,4 glycosidic bond. They are obtained as a result of enzymatic reactions applied to the starch molecule (Sagalowicz and Leser, 2010). One of the most important features of cyclodextrins is the presence of cavities of certain sizes in the core regions. Thanks to hydrophobic interactions, non-polar molecules can be encapsulated in the non-polar inner cavity. Cyclodextrins have many uses in the food industry, especially for the encapsulation of flavours and colours, hydrophobic vitamins (A, E or K) and unsaturated fats, as well as for enhancing the sensory and nutritional properties of foods. Compared to other encapsulation agents, β-cyclodextrin has been reported to better preserve flavour release and quality (Singh et al., 2002, Szente and Szejtli, 2004).

Emulsion method

The emulsion method is used for mixtures consisting of a batch and a continuous phase. The batch phase (cell polymer suspension) is added to the continuous phase (large volume of oil) to form a water-in-oil emulsion and homogenised. In the water-in-oil emulsion formed, water-soluble polymers form small gel structures that are not dissolved in the oil phase (Azagheswari et al., 2015; Martín et al., 2015; Coghetto et al., 2016). While preparing the emulsion, the particle size in the inner phase determines the size of the microcapsules obtained. The formed particles are removed from the liquid solution by filtration and microcapsules are obtained (Heidebach et al., 2012). Vegetable oils such as sunflower, canola, corn, soya are mostly used as continuous phase (Martín et al., 2015; Coghetto et al., 2016). Polymer solutions such as alginate, pectin and carrageenan are also used in the batch phase (Özcan and Altun, 2013). Emulsifiers can be added to the mixture to improve the emulsion. In addition, carregenan, sodium carbosimethyl cellulose, alginate and combinations, chitosan, gelatin, chickpea protein can be used as support materials (Martín et al., 2015). Encapsulation by emulsion method is easy to apply and is often preferred for bacterial encapsulation, especially since the viability rate is preserved. However, it needs to be worked on to form a homogenous emulsion and can be a more costly method compared to methods such as extrusion (Huq et al., 2013; Altamirano-Ríos et al., 2022).

Liposome delivery method

The liposome method has been used in many fields in recent years, especially in food, to coat and protect hydrophilic bioactive components (Aditya et al., 2017). Spherical phospholipid particles that spontaneously form when dispersed in water are called liposomes. Liposomes are spherical bubbles consisting of an aqueous core and one or more bilayer membranes. Due to the ability of liposomes to hold hydrophilic and hydrophobic molecules, they can be added to water-soluble and fat-soluble substances. Liposome encapsulation is widely used to prevent degradation and controlled release of these components (Ghorbanzade et al., 2017). Liposomes have a significant advantage over alternative microencapsulation techniques such as spray drying and fluidized bed coating as they exhibit protective properties, especially in applications with high water activity levels. Other advantages are the long-term preservation of the encapsulated material and its absorption in the gastrointestinal tract, which increases its bioavailability (Fang and Bhandari, 2010). The disadvantages of the method are the inability to produce on a large scale, high cost and lower stability in food processing and preservation (McClements, 2015).

Coacervation

The term coacervation is used in colloidal chemistry to determine the time of coalescent phase separation under controlled conditions by variables of the medium such as pH, temperature, ionic strength, solubility (Timelsana et al., 2019). Coacervation is a solution formed by combining polymers with electrostatically opposite charges, such as proteins and polysaccharides, under certain special conditions. These special conditions include pH, ionic strength, temperature, ratio and molecular weight of the biopolymer used, concentration and degree of homogenisation (Da Silva et al., 2018; Eratte et al., 2018). In the coacervation method, microsphere formation is achieved by accumulating coacervate around the bioactive substance or cell. The resulting coating material envelops the core material in a uniform layer derived from the polymeric solution separated from the liquid phase. After the process, the polymeric solution solidifies and thus the encapsulating structure is formed (Desai and Jin Park, 2005). The coacervation method is a method that does not require organic solvents, high temperature and extreme reaction conditions, is simpler and low cost, and has advantages such as high encapsulation efficiency. The disadvantage of the coacervation method is that the formed coacervate solution is stable in a limited range of pH, temperature and ionic strength (Da Silva et al., 2018; Eratte et al., 2018).

Encapsulation in Food Technology

The controlled release of valuable components during shelf life and the use of microencapsulation to improve the functional properties of the product have gained increasing importance, leading to a rise in studies in this field. In this context, essential oils, lipids, aromatic hydrocarbons, vitamins, colorants, sweeteners, enzymes, microorganisms, microbial metabolites and many other components can be encapsulated using various techniques. The properties of both the core material and the coating material to be encapsulated should be well understood and a suitable method should be chosen accordingly.

Encapsulation has been successfully applied in numerous experimental studies and is used in various fields within the food industry. Meat and dairy products, functional product development, and active packaging are just a few of these areas. Encapsulation has notable applications in dairy technology, particularly in products such as cheese, yoghurt and ice cream. It is used to form and preserve taste and flavor substances, which determine quality criteria and to shorten the ripening period.

The purpose of microencapsulation for probiotic microorganisms used in different products is to maintain the viability of probiotic cells by controlling their release from capsules in harsh environments, such as mechanical processing (e.g. grinding) and exposure to gastric juice during digestion (Frakolaki et al., 2021).

The effect of encapsulated probiotics on increasing the viability level in cheese was investigated by Lopes et al. (2021). The viability levels of encapsulated *L. acidophilus* LA-5 probiotic bacteria added to spreadable ricotta cheese as well as their effects on the quality parameters of the product were reported. Three samples were compared and evaluated during 7 days of storage at 7 °C: one with non-encapsulated cells, one coated with alginate and one coated with alginate/chitosan. Microencapsulation of probiotic cultures showed higher viability, with >6.00 log cfu/mL. Similarly, the viability study conducted under gastrointestinal conditions demonstrated high survival, with 6.00-6.06 log cfu/mL after digestion. Additionally, sensory analysis revealed that probiotic microencapsulated forms were less sticky but softer and more spreadable, with higher moisture content and related efficiency. Statistical analyzes indicated that there was not significant difference between the free and microencapsulated form in terms of liking and purchasing tendency, suggesting that the sensory acceptance of the probiotic product is not impaired by microencupsulation. In another study, it was reported that microencapsulated *L. acidophilus* LA-5 improved the firmness and protein content of yoghurt, significantly reduced spontaneous whey separation and enhanced the physiochemical characteristics of yoghurt (Wang et al., 2018).

L. acidophilus and *Bifidobacterium bifidum* probiotic cultures were encapsulated using extrusion technique and their viability levels were investigated by da Silva et al. (2021). Five samples were prepared for each of two probiotics: a standard formula without probiotic capsules, a formula containing free microorganisms and three formulas containing probiotic capsules at varying ratios (3%, 5% and 10%). The sample with the highest viability rate at the end of storage was used for sensory analyses. The results showed that 5% and 10% concentrations of capsules containing *L. acidophilus* achieved the best results, with 8.00 log cfu/g after 45 days of storage at 5 °C. In contrast, samples containing *B. bifidum* showed insufficient viability, with only 2.00 log cfu/g after 22 days of storage. For evaluating sensory characteristics such as colour, texture, taste, aroma, and general appearance, the unencapsulated standard sample was compared with the formulation containing 10% probiotic capsules. The butter with 10% capsules was preferred by consumers, indicating that this formulation has potential for commercialization.

Recently, changes in the viability levels of bacteria and the quality of Egyptian traditional Kariesh cheese due to the addition of encapsulated probiotics were studied under both product and gastrointestinal conditions. *B. lactis* BB-12, *L. rhamnosus* NRRL B-442, and *L. gasseri* NRRL B-14168 probiotics were encapsulated using the extrusion method with 1%, 3% and 5% rice flour and 3% sodium alginate as coating material. The survival rate of probiotics under in vitro simulated gastrointestinal conditions was found to be 72.91%, 68.43%, 61.27% and 59.23% for microcapsules containing 5%, 3% and 1% rice flour, respectively. For cheese samples, the numbers of *B. lactis* added in free form decreased throughout storage, while higher counts were observed for the microcapsule-added sample containing sodium alginate and 5% rice flour compared to free cells. *B. lactis* counts increased by 0.58, 0.61, 0.98 and 1.09 logarithmic units for probiotics encapsulated with 3% sodium alginate, 1%, 3%, and 5% rice flour respectively. The study concluded that microencapsulation with rice flour significantly protected and improved the viability of the *Bifidobacterium* strain, and that the addition of microcapsules did not alter the chemical properties of the cheese samples (El Sayed, H. S and Mabrouk 2023).

As another application area, the primary challenge in meat products is the risk of oxidation and microbial contamination between lipids and proteins. Encapsulation is used in meat products to protect food additives or beneficial microorganisms from external factors and to maintain their effectiveness for a longer period (Burgain et al., 2011).

In a study, it was reported that the number of coated *L. curvatus* MBSa2 was higher than that of uncoated bacteria during storage, as a result of encapsulating and adding the bacteriocin-producing *L. curvatus* MBSa2 to a fermented meat product (Barbosa et al., 2015). Sidira et al. reported that *L. casei* strain was used in the production of sausage capsules produced as a coating material of wheat proteins. It was stated that under fermentation conditions, the resistance of probiotics increased, they maintained their viability and were suitable starter bacteria for probiotic sausage production (Sidira et al., 2014).

Oliveira et al. (2022) suggested that encapsulation of olive leaf extract (*Olea europaea L.*) would reduce oxidative spoilage in meat products. For this purpose, the leaf extract was encapsulated with gelatin/chitre gum membranes and added to mutton hamburger to reduce oxidative degradation. The leaf extract was encapsulated using gelatine, chitre and gelatine/chitre materials through the complex coacervation method. The results showed that gelatin and gelatin/chitre matrices had higher encapsulation efficiency and antioxidant activity values compared to the matrix containing only chitre, regardless of the encapsulation technique used. Gelatin and gelatin/chitre particles demonstreated a greater capacity to reduce oxidative reactions in hamburger patties, releasing the highest percentages of phenolic compounds during the first two months of storage. The study indicated that the produced capsules could served as alternatives to artificial antioxidants.

There are also successful examples of the encapsulation method in pathogen inhibition. Haidan et al. (2017) encapsulated rosemary essential oil with chitosan and benzoic acid and added it to *Salmonella*-contaminated beef cutlets. Compared to the control group (non-encapsulated rosemary oil), this encapsulated active ingredient was significantly more effective in reducing the number of *Salmonella*. Even at a concentration of 2 mg/g, encapsulated rosemary oil achieved a substantial 6.00 log reduction in pathogens levels. In another study focused on pathogen inhibition, thyme oil was encapsulated in liposomes and added to chicken meat. This application demonstrated a prolonged reduction effect for *Salmonella* compared to the non-encapsulated sample group (Cui et al., 2017).

The use of bacteriophages instead of antibacterial chemical agents for controlling of pathogenic bacteria in foods is increasingly common. In particular, research on using of bacteriophages to control pathogenic bacteria in foods has intensified since the U.S. Food and Drug Administration (FDA) approved their use for controlling of *Listeria monocytogenes* in meat and poultry products in 2006 and added them to the Generally Recognized As Safe (GRAS) list as a food additive (Chatain, 2014).

To eliminate the risk of *Listeria* pathogens, the thermodistribution of temperature-sensitive *Listeria* phages in ready-to-eat meat product was improved by coating with sodium alginate. The encapsulated phage was reported to effectively inactivate *L. monocytogenes* on the surface of the meat (Ahmadi, 2017). Similarly, by Alves et al. (2019), the ϕıbb-pf7a phage was encapsulated with sodium alginate and used to treat chicken fillets infected with *Pseudomonas fluorescens*. The study’s findings indicated that the number of *P. fluorescens* decreased by 2 logarithmic units in the first two days and by 3 logarithmic units by the 5th day of storage, with this effect persisting throughout the storage period.

Ascorbic acid (vitamin C), which is added to foods as an antioxidant and vitamin supplement, is encapsulated due to its oxidative sensitivity. This encapsulation helps protect vitamin C, thereby increasing the shelf life of food by preventing spoilage. The stability of vitamin C is maintained by using microencapsulated vitamin C in baby foods, breads, cereal bars and dairy products (Açu et al., 2014). In a research by Alvim et al. (2016), which examined the encapsulation of vitamin C using spray drying and spray cooling techniques, it was stated that the content in products obtained using encapsulated vitamin C is advantageous compared to those with unencapsulated vitamin C during the production of biscuits. This advantage arises because the content of products made with encapsulated vitamin C is preserved during baking, preventing the formation of dark spots on the biscuit, which is associated with the thermal degradation of this encapsulated active substance during baking.

Aroma and essential oils, being valuable substances, can be encapsulated in various coating materials due to their sensitivity and volatility. In one study, the microencapsulation of allspice essential oil was conducted using the coacervation method with chitosan and kappa-carrageenan as wall materials. It was reported that the DPPH (2,2-Difenil-1-Pikrilhidrazil) free radical scavenging capacity and superoxide anion radical scavenging activity of the microencapsulated allspice essential oil were significantly lower than those of BHT (butyl hydroxy toluene), with chitosan contributing to the antioxidant activity. Additionally, it was determined that the microcapsules exhibited antimicrobial effects against *Candida utilis*, *Bacillus cereus* and *B. subtilis* (Dima et al., 2014).

In another research, coriander essential oil was encapsulated using the spray drying technique with chitosan obtained from the waste shells of crayfish, also known as freshwater lobster. Three samples were compared: crayfish chitosan, free coriander essential oil, and microcapsule coriander essential oil.

The antioxidant activity of the microcapsules was found to be higher than that of free-form coriander oil and crayfish chitosan. It was stated that the microcapsules obtained from this study could be used as antioxidant and antimicrobial agents in the food and pharmaceutical industries (Duman and Kaya, 2016).

According to a recent research report, wheat germ oil, which is rich in valuable fatty acids, was microencapsulated using waste buttermilk from industrial butter production as a crust material. The microcapsules, created using the spray drying method, were subjected to accelerated oxidation conditions (60 °C for 24 hours). It was found that the peroxide numbers, tocopherol, phytosterol and carotenoid amounts in the encapsulated oil were lower than those in the unencapsulated oil. The study's findings suggest that the coating material used can effectively protect the oxidative stability of germ oil, making it a good alternative (Aslan, 2021).

Various studies have also been conducted to develop functional new products through the encapsulation of different components and to extend the shelf life of food using active packaging.

In a study investigating the effects of encapsulated horseradish root juice on the physicochemical properties, oxidative stability and quality of mayonnaise, capsules were producted using the spray drying method with different biopolymeric carriers (maltodextrin/alginate, maltodextrin/guar gum and maltodextrin/guar gum). The highest encapsulation efficiency was achieved with maltodextrin/alginate (58.32%). All treatments resulted in capsules with desirable physicochemical and acceptable sensory properties in the mayonnaise samples. The capsules exhibited high phenol content and strong antioxidant activity. It was concluded that adding these capsules to mayonnaise delays the formation of oxidation products and could serve as an alternative to synthetic antioxidants (Marković et al., 2024). Tosya and Bolek (2022) reported the encapsulation of turnip bioactive compounds and their potential use as a probiotic product in kefir. According to the research findings, the sensory properties of the samples containing 5% turnip microencapsules were rated the highest. Additionally, the total phenolic, anthocyanin, and antioxidant effects of the encapsulated samples were found to be higher compared to the unencapsulated samples.

The antimicrobial properties of the active packaging, made by encapsulating thyme essential oil (*Thymus vulgaris*) in zein ultra-fine fibrous membranes, were investigated for meat storage. Nanocapsules containing thyme oil encapsulated in zein fibers demonstrated high antioxidant capacity, with 98% inhibition using the ABTS method. The membranes with thyme essential oil effectively inhibited the growth of coliforms, *Escherichia coli* and coagulase-positive *Staphylococcus* during storage at 4.5 °C. The study concluded that these nanocapsules could be used in the development of active packaging for meat products and offer a promising alternative to synthetic preservatives (Peixoto et al., 2023).

Examples of other studies where the encapsulation method has been successfully applied are presented in Table 1.

Table 1. The coating material used in encapsulation, the method and some examples of products tested

Core material	Coating material	Coating method	Product used	Source
L. plantarum prk7	sodium alginate, inulin and skim milk powder	extrusion	yogurt	Kowsalya et al., 2023
Lactic acid bacteria	acacia gum	spray drying	cooked meat paste	Perez-Chabela et al., 2013
L. plantarum	wood gum, maltodextrin, gum arabic	emulsion	oaxaca cheese	Rodriguez-Huezo et al., 2014
L. rhamnosus	alginate, gelatin, gellan gum and fructooligosaccharide	extrusion	sausage	Turhan et al., 2017

Table 1. The coating material used in encapsulation, the method and some examples of products tested (Continued)

Rosehip (*rosa canina*) phenolic compounds	maltodextrin and gum arabic	lyophilization	cake dough	Erdem et al., 2021
Vanillin	maltodextrin, casein, gelatin	lyophilization	biscuit	Özkan, 2021
Olive seed antioxidants	chitosan	lyophilization	in vitro digestion test	Taş and Ötleş, 2021
Citrus peel essential oils	sodium caseinate and maltodextrin	spray drying	fish oil powder	Uçar, 2020
Propolis	gelatin,hydroxypropyl methylcellulose	lyophilization	ın vitro digestion test	Zainal, 2021
Spirulina	sodium alginate	spray drying	fresh pasta	Zen, 2020

CONCLUSION

Encapsulation is an alternative method for controlled production systems that addresses significant challenges in the food industry. This method aids in the preservation and controlled release of perishable food components and various additives during food processing. However, it faces challenges such as the development of procedures, time, cost and the selection of non-toxic materials. Although the method has been applied in the food industry, many studies remain at the laboratory scale. It is recommended that academic research be expanded to guide larger-scale encapsulation applications in the future. This review focuses on current studies in the field and based on the progsess made to date, it is anticipated that future research will grow, meeting consumer demands with the functional products enriched with nutritious, bioactive compounds and extended shelf life.

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