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REVIEW PAPER

MICROENCAPSULATION AS AN INNOVATIVE TECHNIQUE FOR THE PREPARATION OF HIGH-ADDED VALUE BAKERY PRODUCTS – A REVIEW

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Abstract

Bioactive compounds (polyphenols, carotenoids, etc.) are natural food components that provide nutritional and health benefits. Their use has increased in recent years in the food industry due to consumer concerns about the safety of synthetic ingredients. Bioactive compounds are added to food products to flavor, color, preserve and improve health benefits, but the main problem is their susceptibility to various processing and storage conditions. Microencapsulation is a useful technology that protects these compounds from degradation, increases their bioavailability, masks their undesirable characteristics and improves shelf life. Appropriate selection of encapsulation techniques and conditions, such as carriers, carrier to substrate ratio, drying temperature, feed flow rate, inlet air temperature, can affect encapsulation efficiency and final product quality. Therefore, the purpose of this review article is to collect the latest contributions and findings on microencapsulation performance and recent advances in microencapsulation processes, as well as their future prospects in the food industry.

Keywords: microencapsulation, bakery products, bioactive compounds, wall material, antioxidant activity

Introduction

The demand for functional and health-promoting food products is steadily growing in modern diets. As a result, this trend has captured the interest of food scientists, who are incorporating functional ingredients into diverse food formulations (Nikmaram *et al.*, 2017; Carvalho Barros *et al.*, 2020). Functional foods are nutritional products that, in addition to their basic nutritional value, provide additional health benefits such as supporting the immune system, improving

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digestion, or reducing the risk of chronic diseases due to their content of biologically active compounds (Granato *et al.*, 2020). Flour-based products are the most commonly consumed among confectionery products in general. Due to the popularity and growing interest in the concept of functional food, the relationship between food and health is increasingly influencing food innovation. As the role of diet in the prevention of diseases such as cancer, cardiovascular disease, and obesity becomes more apparent, many consumers are increasingly looking to functional foods to improve their diets. Consequently, there is a trend to seek natural raw materials rich in dietary fiber, and essential fatty acids and with high antioxidant capacity as functional ingredients for the food industry (Mildner-Szkudlarz *et al.*, 2013). About baked goods, these efforts are particularly important as children and young people consume these products with gusto and very frequently, and sometimes uncontrollably. Uncontrolled consumption of high-calorie products in unnecessary quantities, especially confectionery, can harm a balanced diet and lead to obesity. New products should have improved health properties and at the same time, they should taste and look like traditional confectionery products that are popular and regularly consumed. Flour-based confectionery products are well suited for enrichment with ingredients with pronounced functional-health properties. In this sense, the study offers the possibility to improve such products through different approaches and to present new trends in the development of functional flour-based confectionery by using different additives that could reduce the energy value, improve the nutritional and biological values, and develop products with pronounced functional properties.

Application of microencapsulation in bakery products

In most food products, fats and oils, aromatic compounds and oleoresins, vitamins, minerals, colorants, and enzymes are encapsulated and show promise for the development of functionally active food products. The advantages of microencapsulation are its ease of administration, stabilized active component, increased acceptability, protection, controlled release, and creation of novel functional food (Oručević Žuljević *et al.*, 2020). The purpose of the process of microencapsulating bioactive compounds is to stabilize them, allow them to be in powder form, mask unpleasant tastes or flavors, and improve bioavailability. This technology allows the bioactive components to be covered and protected by completely enveloping them with a physical barrier. It is a way of packaging solid, liquid, or gaseous materials in small capsules that release their contents at controlled rates over extended periods and under defined conditions. Since confectionery is a widely consumed product, it is therefore an ideal food for fortification (Shrestha *et al*., 2012). Incorporation of microencapsulated vitamins into a food matrix contributes to improving the nutritional value of products, reducing unpleasant flavors, allowing the release of nutrients over time, increasing high temperature and moisture stability, and reducing the interaction of each nutrient with other ingredients (Jeyakumari *et al*., 2016). Microencapsulation represents a successful means of increasing lycopene stability. Furthermore, it has been found that microcapsules with lycopene obtained by spray drying release pigment and color in cake samples homogeneously (Rosha *et al*., 2012).

The encapsulated substance is the core material, active component, internal phase, or payload. The material that surrounds and protects the core is termed the wall material, coating, membrane, shell, carrier, outer phase, or matrix. Encapsulates are generally classified into two primary types: reservoir-type and matrix-type (Zuidam and Shimoni, 2010). In the reservoir type, the active agents are contained in a core surrounded by an inert protective layer, also referred to as the core-shell type. In the matrix type, the active substance is evenly distributed or dissolved within an inert polymer. Microcapsules are prepared by different methods. Microencapsulation can be categorized into physical and chemical methods. The physical methods encompass spray drying, rotating disk atomization, fluidized bed coating, coextrusion, and coating techniques. On the other hand, the chemical methods involve simple and complex coacervation, intermediate polymerization, and phase separation (Zuidam and Heinrich, 2010). Some high-value-added components, such as essential oils, have significant properties from a nutritional and medicinal point of view. Antimicrobial activity is particularly important for use in the production of functional foods and allows for an extended shelf life of the final product. Furthermore, their strong and atypical flavors and odors can be successfully masked by encapsulation (Vinceković *et al.,* 2017). A typical example of this is the study on the use of encapsulated thyme (Thymus vulgaris) oil as a natural food preservative that can be applied to sweets to extend their shelf life and avoid the use of synthetic preservatives (Goncalves *et al.,* 2017). Due to the numerous application possibilities and different methods that allow the most suitable solutions to incorporate certain functional ingredients into the food matrix, microencapsulation is a promising biotechnological method for enriching flour-based confectionery products (Table 1).

Probiotics in bread

Probiotics such as *Lactobacillus* are encapsulated in bread to protect them from high baking temperatures. The microencapsulation ensures that probiotics survive the baking process, providing gut health benefits. This technique improves probiotic survival by over 50%, offering a significant enhancement in their health benefits (Kailasapathy, 2012).

Flavor protection in cakes and muffins

Essential oils, like lemon and cinnamon, are encapsulated to protect their volatile compounds during the baking process. This ensures that flavor retention in cakes and muffins exceeds 90% post-baking, maintaining the desired sensory experience for consumers (Burgess *et al.,* 2015).

Nutritional fortification in biscuits

Omega-3 fatty acids, along with vitamins A and D, are encapsulated in biscuits to protect these sensitive nutrients from degradation during baking. Microencapsulation increases the bioavailability of omega-3 fatty acids by 40%, boosting the nutritional benefits of the final product (Zhao *et al.,* 2017).

Table 1. Current applications and metrics in bakery products.

Bakery Product	Encapsulated Ingredient	Benefits	Microencap-sulation technique	Performance indicators
Bread	Probiotics (*Lactobacillus*)	Enhanced gut health, protection from baking temperatures (up to 180°C)	Gelation, coacervation	Increased shelf life of probiotics by 50%, improved viability post-baking (Kailasapathy, 2012)
Cakes and muffins	Essential oils (e.g., lemon, cinnamon)	Preservation of volatile flavors, prevention of flavor loss during baking	Spray drying, solvent evaporation	Retention of 90% of initial flavor after baking (Burgess et al., 2015)
Biscuits and crackers	Omega-3 fatty acids, vitamins A and D	Improved nutritional profile, stable delivery of nutrients during processing	Fluidized bed coating, extrusion coating	40% higher bioavailability of encapsulated omega-3 in biscuits (Zhao et al., 2017)
Pastries and croissants	Vitamin C, antioxidants	Protection of sensitive nutrients, sustained release throughout consumption	Polymer-based microcapsules	30% increase in vitamin C retention after baking (Burgess et al., 2015)
Gluten-free products	Iron, folic acid, calcium	Fortification of gluten-free products, enhanced nutrient delivery without compromising taste	Spray drying, electrostatic deposition	20% increase in calcium absorption (Zhao et al., 2017)
Bread	Iron, Zinc, Folic Acid	Fortification of nutrients, improved bioavailability without affecting taste or texture	Spray drying, coacervation	25% higher absorption of iron and folic acid (Xu et al., 2019)
Cakes	Omega-3 fatty acids	Enhanced heart health, stability of omega-3 during baking, retention of nutrients	Freeze drying, fluidized bed coating	Retention of 75% omega-3 after baking (García et al., 2020)
Biscuits	Probiotics (*Bifidobacterium*)	Improvement in gut health, prevention of bacterial degradation during baking	Microencapsulation in starch-based matrices	50% of probiotics survive baking process (Gänzle et al., 2015)
Cookies	Antioxidants (e.g., Vitamin E)	Protection of antioxidants, enhanced stability, prevention of oxidation	Complex coacervation, spray drying	40% retention of antioxidants post-baking (Gómez-Estaca et al., 2016)
Gluten-Free Cakes	Calcium, Magnesium	Nutrient enrichment for gluten-free consumers, better bioavailability	Emulsifier-based encapsulation	30% increase in calcium absorption (Fiszman et al., 2014)
Pastries	Flavonoids (e.g., Quercetin)	Protection from heat, enhanced health benefits, anti-inflammatory properties	Nanoencapsulation, polymer encapsulation	20% higher retention of quercetin after baking (Faria et al., 2018)
Croissants	Natural flavors (vanilla, chocolate)	Preservation of delicate flavors, longer-lasting aroma and taste	Spray drying, coacervation	90% retention of flavors post-baking (Thomazini et al., 2019)
Muffins	Vitamin D3	Fortification of bakery products with Vitamin D, improved absorption	Lipid-based encapsulation	50% increase in Vitamin D bioavailability (Ibrahim et al., 2017)

Vitamin protection in pastries

Vitamins and antioxidants, such as Vitamin C, are encapsulated in polymer-based microcapsules to ensure they are not destroyed by heat during baking. Microencapsulation preserves up to 30% more Vitamin C compared to non-encapsulated products, ensuring better nutrient retention (Burgess *et al.*, 2015).

Fortification of gluten-free products

Gluten-free products are often fortified with nutrients like calcium and iron, which are crucial for those following gluten-free diets. Microencapsulation guarantees that these nutrients are delivered more effectively, with studies showing up to a 20% increase in calcium absorption for consumers of microencapsulated gluten-free products (Zhao *et al.*, 2017).

Antioxidant protection in cookies

Antioxidants like Vitamin E are encapsulated in cookies to maintain their stability and prevent oxidation during baking. The encapsulated antioxidants retain up to 40% of their activity post-baking, improving the shelf life and nutritional quality of the cookies (Gómez-Estaca *et al.,* 2016).

Fortification of gluten-Free cakes

Calcium and magnesium are encapsulated in gluten-free cakes to provide additional nutritional value, as these nutrients are often deficient in gluten-free diets. Microencapsulation allows for better absorption of these nutrients, with studies showing a 30% increase in calcium absorption by consumers (Fiszman *et al.,* 2014).

Flavonoids in pastries

Flavonoids such as quercetin are encapsulated in pastries to protect them from heat degradation and enhance their health benefits. This microencapsulation method results in a 20% higher retention of quercetin after baking, improving its bioavailability and anti-inflammatory effects (Faria *et al.*, 2018).

Flavor protection in croissants

Natural flavors like vanilla and chocolate are encapsulated in croissants to preserve their delicate taste and aroma during baking. Microencapsulation helps retain 90% of the flavors post-baking, ensuring a long-lasting sensory experience for consumers (Thomazini *et al.*, 2019).

Vitamin D3 fortification in muffins

Vitamin D3 is encapsulated in muffins to improve the bioavailability of this essential nutrient, which is often deficient in diets. Microencapsulation increases the absorption of Vitamin D by 50%, offering significant health benefits to consumers (Ibrahim *et al.,* 2017).

Microencapsulation technology is increasingly used in the bakery industry to improve the functionality and quality of various products. It involves enclosing active ingredients (e.g., vitamins, minerals, flavors, essential oils, probiotics) within a protective coating, allowing for their controlled release and protection from environmental factors such as heat, moisture, and oxygen during processing. This technique provides several advantages, including extended shelf life, enhanced sensory properties, and the ability to deliver nutrients effectively.

Microencapsulation of biologically active substances

Functional foods are enriched with bioactive ingredients such as proteins, vitamins, minerals, antioxidants, and probiotics, which offer additional health benefits beyond basic nutrition. However, these sensitive ingredients present challenges in food formulation. Encapsulation technology provides an effective solution by protecting these bioactives and allowing the development of innovative food products with enhanced properties (Schrooyen *et al.,* 2001). Microcapsules typically range in size from 2 to 5000 µm. In the food sector, microencapsulation serves multiple purposes, including safeguarding the core substance from degradation and reducing its evaporation into the surrounding environment. It also modifies the properties of the original material for easier handling, enables controlled, gradual release of the core ingredient, masks undesirable tastes or odors, and keeps reactive components of a mixture separated (Desai and Park, 2005).

Protection of omega-3 fatty acids through microencapsulation

Omega-3 fatty acids are a group of polyunsaturated fats that the body cannot produce on its own but are crucial for various aspects of human health. The key omega-3 fatty acids include alpha-linolenic acid, eicosapentaenoic acid, and docosahexaenoic acid. Because of their unsaturated structure, these fatty acids are prone to oxidation, leading to the formation of hydroperoxides and undesirable flavors, which can negatively impact consumer acceptance. To address the challenges mentioned earlier, Pratibha *et al.* (2014) explored the use of microencapsulation techniques. Various methods for microencapsulating omega-3 fatty acids are outlined in Table 2.

Polyphenol encapsulation technology

Flavors are crucial in food products as they significantly impact consumption and overall satisfaction. There is a growing market demand for natural flavor ingredients as replacements for synthetic alternatives. However, liquid food flavors are challenging to incorporate into food systems and are vulnerable to degradation from oxygen, light, and heat. Encapsulation technology addresses these issues by effectively shielding aromatic compounds from damage, oxidation, and migration within food products. Essential oils, which are volatile and complex mixtures with strong aromas derived from aromatic plants, possess various biological properties, such as antioxidant, antimicrobial, antiviral, and anti-inflammatory effects. Examples include oils from ginger, garlic, cinnamon, and other plants (Bennick, 2002). A group of researchers found that plant polyphenols could help slow the development of cancer, diabetes, and osteoporosis, while also lowering the risk of cardiovascular diseases (Scalbert *et al.,* 2005). Table 3 presents the various methods employed for the encapsulation of polyphenols.

Table 2. Techniques and encapsulating materials for omega-3 fatty acid microencapsulation

Encapsulation method	Wall materials used	Applications	Advantages
Spray drying	Gelatin, maltodextrin, casein, lactose, sodium caseinate, dextrose equivalent, cyclic dextrin, methylcellulose, hydroxypropyl methylcellulose, n-octenyl succinate, modified starch/glucose syrup, trehalose, beet pectin, arabic gum, corn syrup solids, egg white powder	Used for encapsulating omega-3 fatty acids (e.g., fish oil), vitamins, and other sensitive compounds.	Effective for mass production; suitable for water-soluble and oil-soluble materials; maintains stability of sensitive compounds.
Spray drying	Whey protein isolate, gum arabic, lecithin, maltodextrin, whey protein concentrate, modified starches, tapioca starch, and waxy corn	Commonly used for encapsulating plant oils like linseed oil.	Enhances the stability of sensitive ingredients, such as oils, and allows for controlled release.
Freeze drying	Sodium caseinate, carbohydrates, egg white powder, gum arabic, lactose, maltodextrin	Applied for the encapsulation of volatile or sensitive oils like fish oil.	Preserves bioactive compounds by minimizing degradation due to heat; improves storage and shelf life of the active compounds.
Freeze drying	Gelatin	Applied for encapsulation of bioactive oils like linseed oil.	Protects sensitive bioactive components and prevents oxidation during storage.
Simple coacervation	Hydroxypropyl methylcellulose	Commonly used for encapsulating probiotics, enzymes, and vitamins.	Efficient encapsulation of active ingredients in aqueous systems; ideal for hydrophobic substances.
Complex coacervation	Gelatin-gum arabica with transglutaminase	Widely used for probiotic encapsulation to protect them from harsh	Offers a high degree of encapsulation efficiency; provides controlled release in

		conditions like stomach acid.	gastrointestinal systems.
Double emulsification and subsequent enzymatic gelling	Soy protein, whey protein, whey protein, sodium caseinate, transglutaminase	Typically used for sensitive oils like fish oil, in functional food formulations.	Enables controlled release and protects sensitive compounds from oxidation and degradation.
Ultrasonic atomization and freeze-drying	Chitosan	Used for encapsulating omega-3 oils in nutraceutical and functional food products.	High encapsulation efficiency; suitable for small-scale or specialized applications.
Spray granulation and film coating with fluidized bed	Soya soluble polysaccharide and maltodextrin	Applied to create stable, small particles of bioactive ingredients like fish oil, often used in dietary supplements.	Suitable for high-throughput production; enhances product uniformity and stability over time.

*Source: Pratibha *et al.*, 2014

Encapsulation of vitamins and minerals

Both fat-soluble (e.g., vitamins A, D, E, and K) and water-soluble vitamins (such as ascorbic acid) can be protected through microencapsulation (Wilson and Sahah, 2007). Iron, an essential nutrient for human health, is crucial for various bodily functions, and insufficient intake can lead to deficiencies. One approach to addressing this issue is iron fortification in foods. However, its absorption can be hindered by interactions with certain food compounds like tannins, phytates, and polyphenols. Additionally, iron accelerates oxidative reactions in fatty acids, vitamins, and amino acids, which can degrade sensory qualities and lower nutritional value. Microencapsulation offers an effective solution to minimize these adverse effects and enhance nutrient stability.

Encapsulation of microorganisms

Probiotic bacteria are live microorganisms that provide health benefits to their host, whether human or animal. They play a key role in the development of functional foods, particularly in the dairy industry (Sanders, 2003). Several microencapsulation techniques are used to protect probiotics, including spray-coating, spray-drying, extrusion, emulsion, and gel particle technologies such as spray-cooling. Among these methods, spray-drying and gel particle formation are the most widely applied for probiotic encapsulation (Champagne and Patrick, 2007). Various wall materials utilized for microorganism microencapsulation are listed in Table 4.

Table 3. Techniques and encapsulation materials for polyphenol encapsulation.

Methods	Wall material used	Polyphenols	Advantages	Disadvantages	Applications
Spray drying	Maltodextrin, gum arabica, chitosan, citrus fiber, colloidal silica, maltodextrin and starch, sodium caseinate-soy lecithin, skim milk powder, whey protein concentrate, gelatin	Extracts of black carrot (anthocyanins), procyanidins, olive leaf, hibiscus (anthocyanins), soybean, grape seed, apple polyphenols, olive leaf, oregano essential oil, peppermint oil, cardamom oleoresin, and black pepper oleoresin	High encapsulation efficiency, suitable for a wide range of polyphenols, easy scaling.	Can lead to loss of volatile compounds, heat-sensitive polyphenols may degrade.	Food and beverage products, functional foods, nutraceuticals, flavor protection.
Coacervation	Calcium alginate, chitosan, gelatin (type A), glucan, chitosan and carragenan	Currant extract	Excellent for controlled release, biocompatible materials.	Requires precise conditions for phase separation, possible instability in certain formulations.	Pharmaceutical applications, functional food ingredients, flavor delivery systems.
Cocrystallization	Sucrose syrup	Orange peel oil	Simple method for flavor encapsulation, can enhance stability.	Limited to certain types of compounds, may require additional stabilization methods.	Flavor encapsulation in confectionery and beverages, food additives.

Table 3. (continued) Techniques and encapsulation materials for polyphenol encapsulation.

Methods	**Wall material used**	**Polyphenols**	**Advantages**	**Disadvantages**	**Applications**
Lyophilization	Maltodextrin	Anthocyanin, bilberry extract, hibiscus anthocyanin, orange oil	Maintains the integrity of sensitive compounds, no heat involved, ideal for heat-sensitive polyphenols.	Time-consuming, requires specialized equipment, expensive compared to other methods.	Used in pharmaceuticals, herbal products, functional foods, and nutraceuticals.
Extrusion	Corn syrup, glycerin, sodium alginate	Citrus oil, clove oil, thyme oil, cinnamon oil	Suitable for large-scale production, allows the incorporation of polyphenols into solid matrices.	Limited to specific ingredients, high temperatures may affect polyphenol stability.	Confectionery, snack foods, fortified cereals, and functional ingredients in food.
Electrostatic extrusion	Calcium alginate gels	Ethyl vanillin (3-ethoxy-4hydroxybenzaldehyde)	Provides precise control over particle size and distribution, effective for sensitive compounds.	Complex process, requires specialized equipment, limited scalability.	Used for encapsulating flavors, fragrances, and bioactive compounds in food and beverages.

*Source: Zhongxiang and Bhesh, 2010; Bakry *et al.*, 2016

Table 4. Techniques and encapsulation materials for microorganism microencapsulation microorganisms.

Encapsulation technique	Wall material	Microorganisms	Additional information
Additional Information	Various coating materials (gelation system)	Not specified	Particles are tumbled in a pan, generating droplets of 100-5,000 µm. Air suspension methods used for better control.
Air-Suspension Coating	Coating solutions or melts	Not specified	Particles are suspended in upward air, allowing multiple passes to coat and achieve uniform particle formation.
Spray-Drying	Polymer solution/melt	Not specified	Active material dissolved/suspended and trapped in dried particles. Short drying time for labile materials like probiotics.
Centrifugal Extrusion	Wall solution or melt	Not specified	A jet of core liquid surrounded by a wall solution/melt breaks into droplets, forming capsules with limited viscosities.
Interfacial Polymerization	Polycondensation reactants (acid chloride)	*Bifidobacterium* spp., probiotics	Thin flexible walls form rapidly at the interface of emulsion droplets; used for encapsulating sensitive probiotics.
In-situ Polymerization	Polyethylene, cellulose fibers	Not specified	Monomer polymerization on particle surfaces to form uniform coating. Coating thickness ranges from 0.2-75 µm.
Matrix polymerization diisocyanate	Various polymers	Probiotics	Core material imbedded in polymeric matrix, often via spray-drying; can be triggered by chemical change to solidify matrix.
Alginate-starch encapsulation	Calcium alginate, Hi-Maize starch	*Lactobacillus acidophilus,*	Cryo-protectant glycerol used to improve survival under

		Bifidobacterium spp.	freezing; enhanced survival of encapsulated probiotics in yogurt.
Direct compression encapsulation	Hydroxypropyl cellulose, milk proteins	*Lactobacillus acidophilus*	Compression coating improves storage stability; impacts cell viability depending on compression pressure.
Whey protein gel particles	Whey protein isolate	*Lactobacillus acidophilus*	Encapsulated probiotics using denatured whey protein; significant survival rates after processing and storage.
Prebiotic encapsulates	Prebiotic fiber (inulin, FOS, etc.)	*Lactobacillus rhamnosus*	Prebiotics like inulin help boost probiotic growth and increase survival during storage and after formulation.
Alginate-coated gelatin microsphere	Alginate, gelatin	*Bifidobacterium adolescentis*	Alginate cross-linked with genipin to improve survival during exposure to acidic and bile conditions.
Interpolymer complex in CO_2	Poly (vinyl pyrrolidone)-poly (vinyl acetate)	*Bifidobacterium longum*, indomethacin	Supercritical CO_2 used for encapsulation; protects probiotics from adverse conditions and ensures controlled release in the GI tract.

*Source: Vidhyalakshmi *et al.*, 2009

Encapsulation of protein hydrolysates and peptides

Nutritional protein hydrolysates and peptides are valuable functional food components. However, their use in food products can be challenging due to their bitter taste, high moisture absorption, and interactions with the food matrix. Encapsulation offers an effective solution to these issues (Erdmann *et al.*, 2008). Various carriers, including proteins, polysaccharides, and lipids, have been utilized for their encapsulation. Protein- and polysaccharide-based carriers help mask bitterness and reduce moisture absorption, while lipid-based carriers improve the bioavailability and stability of the encapsulated peptides.

Encapsulation is a technique that entails enclosing a particle, compound, or active ingredient within a protective material known as the wall material. This method is extensively applied across different industries to safeguard, stabilize, and prolong the shelf life of sensitive components, preventing their degradation over time (Risch, 1995). In the food industry, encapsulation is utilized to protect enzymes, flavors, colors, and aromas, enhancing their stability, improving texture, and enabling controlled release for better functionality in food products (Nedovic *et al.*, 2011). In the pharmaceutical industry, encapsulation is employed to enhance the administration of oral medications and promote their efficient absorption in the body (Shahidi and Han, 1993). Encapsulation can be carried out using either hot methods, such as solvent evaporation, spray drying, and melt extrusion, or cold methods, including spray cooling and lyophilization. Among these techniques, spray drying is the most commonly applied (Mohammedet *al.*, 2020). The chosen encapsulation technique determines the particle size, producing either nanoparticles (capsules or spheres) ranging from 10 to 1000 nm or microcapsules (mononuclear, multinuclear, or matrix) with sizes between 3 and 800 µm (Tolve *et al*., 2016). The capsule material refers to the protective matrix that protects the core material, such as particles, substances or compounds, during the encapsulation process and subsequent processing. It must have the ability to withstand mechanical stress and environmental conditions (e.g., moisture, temperature, and water activity) (Coimbra *et al.*, 2020). In spray-drying processes, the wall material selected must ensure the stability and shelf life of the encapsulated particle, substance or compound while being cost-effective in terms of yield and encapsulation efficiency (Anandharamakrishnan and Ishwarya, 2015).

Polysaccharides

Polysaccharides are chains of simple sugars linked by glycosidic bonds. They are synthesized naturally by plants (*e.g*. starch and cellulose), animals (e.g. chitosan and chitin) and microorganisms (*e.g*. dextran and gellan gum) to produce energy and perform physiological and structural functions (Aravamudhan *et al.*, 2014). The most commonly used polysaccharides are starch, maltodextrin, chitosan, dextran, carrageenan and gums. The main characteristics of each are as follows:

Starch is a complex polysaccharide composed of amylose and amylopectin derived primarily from tubers (*e.g*. potato, cassava and sweet potato) and cereals (*e.g*. maize, sorghum, wheat, rice, rye, oats and barley). This carbohydrate consists of glucose monomers with free hydroxyl groups (-OH), giving it a highly hydrophilic helical structure (Egharevba, 2019). Starch finds application in various foods due to its physicochemical properties such as solubility, viscosity, texture and thermal stability.

Maltodextrin is a polysaccharide derived from the hydrolysis of starch (from corn, rice, wheat, tapioca, sorghum, barley, etc.) with a dextrose equivalent value of less than 20 (Parikh *et al*., 2014). It is used as a fat replacer in dairy products, meat and pasta due to its ability to form gels, hygroscopicity, solubility, viscosity and sweetness (Chavan *et al*., 2016).

Chitosan is a structural polysaccharide extracted from microorganisms (such as fungi and algae), marine animals (such as crustaceans and molluscs) and insects (such as scorpions and spiders) or obtained by chemical deacetylation of chitin (Rinaudo, 2006). Chitosan is highly valued for its antibacterial, antifungal and antiviral activity attributed to its cationic polyelectrolyte nature. It also possesses the ability to form gels due to its viscosity, plasticity and solubility (Lizardi-Mendoza *et al.,* 2016).

Carrageenan is a sulfated polysaccharide extracted from red algae such as *Kappaphycus* and *Eucheuma*. Carrageenan has no proven nutritional value, but finds special use in the food industry due to its gelling, stabilizing, binding and thickening properties. It is used in products such as jellies, dressings, fat replacers and pet food (Loureido *et al*., 2017).

Gums are water-soluble polysaccharides that have no specific classification but are recognized for the production of viscous-sticky dispersions at low concentrations. Gums are derived from algae (such as agar and alginates), microorganisms (such as gellan and xanthan) or higher plants (such as pectin and arabinogalactans). The gel-forming properties of gums are due to their affinity for water, which allows rapid hydration and volume increase. The degree of hydration results in different rheological properties that allow their application in food products as texture enhancers, stabilizers, and coatings (BeMiller, 2019).

Proteins

Proteins are macromolecular structures composed of amino acids and play a vital role in all biological processes of living organisms. Proteins are part of the human diet as they are present in varying proportions in all animal and plant products that are consumed. These macromolecules are valued in industry for their gel-forming and foaming properties, especially in the food industry, which allows their application to enrich existing products (Lafarga, 2018). The use of proteins in microencapsulation processes is possible due to their ability to form solid matrices, especially with proteins such as gluten, isolated proteins (e.g. soy and pea proteins), caseins, whey proteins and gelatin (Wandrey *et al.,* 2010). Their main characteristics are described below:

Gluten is a mixture of insoluble proteins found in cereals such as wheat, rye and barley. The rheological properties of gluten facilitate the retention of air in dough, making it particularly useful in processed food products such as bread, pasta, biscuits, cakes and other fermented products (Day *et al.*, 2006).

Casein is a group of proteins found in milk. Casein can be obtained by precipitation of milk at pH 4.6, electrophoresis or membrane processes. It can be applied in the formulation of nano and micro materials, food additives and biodegradable films as it can form gels when interacting with other polymers (Wusigale *et al.,* 2020).

Gelatin is a water-soluble protein derived from the hydrolysis of collagen, an insoluble product found in animal cartilage, skin, fibers, and tendons. Gelatin is classified as a hydrocolloid because of its high water-holding capacity. Its viscosity is its main property that allows it to texture, thicken, stabilize emulsions, create foams and form thermo-reversible gels. Gelatin is free of sugars and fats and rich in proteins (Haug *et al*., 2011).

Whey proteins are by-products produced during the processing of dairy products. They can be classified into protein concentrates and protein isolates. In addition to their nutritional value, whey proteins have binding and gelling properties and are able to stabilize foams and form emulsions (Jovanovic *et al.*, 2005).

Lipids

Lipids are organic molecules that play important biological and structural roles in living organisms. They are characterized by their insolubility in water. In the food industry, they are used as edible oils and coatings (Tao, 2007). Among lipids, waxes are the most commonly used in encapsulation by spray drying. Waxes are soft or sticky substances that form on the surface of plants (*e.g*., carnauba and candelilla wax), as well as on the body of animals (*e.g*., whales and sheep) and insects (*e.g*., bees). Waxes may contain fatty acids, primary and secondary alcohols, aldehydes, sterol esters, ketones, triacylglycerols and triterpenes. Waxes exhibit high hydrophobicity and resistance to hydrolytic degradation (Vanhercke *et al.*, 2013).

Bioactive compounds are secondary metabolites derived from plants and their importance lies in their wide range of properties that promote human and animal health, such as antioxidant, antimicrobial, antibacterial, anti-inflammatory and anticancer effects (Uwineza and Waskiewicz, 2020). The most valuable bioactive compounds for the industry include essential oils, carotenoids, fatty acids, phenolic acids and flavonoids. These metabolites are extracted using methods such as solvent extraction, electrical pulses, hydrolysis, membrane systems and others. However, the main challenge arises when it comes to their storage. Bioactive compounds can be volatile, thermolabile, and unstable, requiring protection to maintain their bioactivity (Bazana *et al*., 2019).

Starch is a carbohydrate that can undergo modifications to interact with hydrophilic and hydrophobic compounds. García-Gurrola *et al.* (2019) demonstrated that modified starch by phosphorylation, esterification, and acetylation techniques improved the retention and stability of encapsulated phenolic compounds extracted from red sorghum. Acetylation of starch was found to increase its hydrophobic nature and improve the retention of lipid bioactive compounds. Márquez- Gómez *et al.* (2017) reported that the mixture of natural starch with modified starches (acetylated starch and maltodextrin) improved the stability and prevented the oxidation of essential orange oil. This improvement is due to a decrease in diffusivity and an increase in hydrophobicity by acetylation of the starch.

The effectiveness of carrageenan encapsulation is influenced by the type of component it encapsulates. In general, any type of carrageenan is suitable for encapsulating aqueous extracts. However, the study by Marín-Peñalver *et al.* (2021) showed that encapsulation of lipid components was insufficient. The interaction between carrageenan and lipids is very poor, resulting in incomplete homogenization and components remaining outside the capsules.

Correâ-Filho *et al.* (2019) encapsulated β-carotene with gum arabic and evaluated the encapsulation yield at different concentrations (5-35%) and temperatures (110-200°C). The study reported that temperature affected antioxidant activity only when the percentage of wall material was low, while the highest yield was obtained using intermediate levels of temperature and gum concentration. Morphology is affected by temperature, with lower temperatures resulting in microspheres with higher void content and rougher surfaces. In addition, lower inlet temperatures result in smaller particles, which may be due to the increased swelling and/or shrinking that occurs when water evaporates slowly.

Fu *et al.* (2020) observed that capsules formed with protein isolate during vitamin E encapsulation showed irregular spherical shape with surface cracks and roughness. This irregular morphology is due to the non-uniform dispersion of the droplet during the spray-drying process. The authors summarize that the inclusion of polysaccharide in the protein dispersion improves homogenization, resulting in a more stable particle size. In another study by Khalilvandi-Behroozyar *et al.* (2020), the encapsulation of polyunsaturated oil, particularly fish oil, with casein was evaluated. The findings showed that effective oil protection was achieved when casein was used in a ratio equal to or less than the oil, such as 1:1 or 1:2 (casein to oil). Furthermore, the combination of polysaccharide with the protein increases the encapsulation efficiency and extends the shelf life of the encapsulated components.

Lipids are wall materials that are rarely used alone. The role of lipids in encapsulation processes is to improve the gelling properties and viscosity of polysaccharide- and protein-based dispersions (Chauhan *et al.*, 2005). Some studies use lipid materials to create emulsions that are subsequently subjected to the spray drying process using another wall material. For example, Salminen *et al.* (2019) developed two emulsions: one based on triacylglycerol with lecithin and saponins and the other based on triacylglycerol and the compound to be encapsulated (fish oil). The authors combined the two emulsions to induce crystallization and then mixed them with maltodextrin as wall material for the drying process.

Application of microencapsulated bioactive ingredients in food products

Microencapsulation provides several benefits for encapsulated materials, enhancing their stability and functionality. A summary of encapsulated food ingredients and their applications is presented in Table 5. Controlled release refers to a technique that ensures the active compounds reach the target site at a specific rate and time. Its primary goals include minimizing the loss of sensitive compounds like vitamins and minerals during processing and storage, optimizing their absorption, and improving overall effectiveness. The most widely used controlled release mechanisms involve thermal and moisture-triggered release (Risch, 1995). The primary mechanisms governing core release include pH changes, temperature variations, solvent action, diffusion, degradation, swelling, and osmotic pressure activation. In most cases, a combination of these mechanisms is employed to achieve effective and controlled release of the core material (Desai and Park, 2005).

In diffusion-controlled release, the active ingredient is released through the polymer either by diffusion within the polymer (in reservoir systems) or through existing pores (in matrix systems). In tank systems, the active agent is released via diffusion into the tank, where it dissolves between the carrier fluid and the baffle. The release rate from a reservoir system is influenced by factors such as the permeability, surface area, and thickness of the barrier (Azevedo and Reis, 2005).

Table 5. Application of microencapsulated bioactive ingredients in food products.

Type of encapsulated bioactive ingredients	**Purpose**	**Benefit of encapsulation**	**Applications**
Lipids (fish oil, linolenic acid, rice bran oil, sardine oil, palmitic acid, seal oil)	To avoid oxidative breakdown during processing and storage	Preserves nutritional quality and extends shelf life	Dietary supplements, food fortification
Natural flavourings (citrus oil, peppermint oil, onion oil, garlic oil, spice oleoresins)	To convert liquid fragrances into stable, free-flowing powders that are more convenient to manage	Provides stability and prevents loss of aroma	Food flavorings
Vitamins (Fat-soluble: vitamin A, D, E and K. Water-soluble: vitamin C, vitamin B1, vitamin B2, vitamin B6, vitamin B12, niacin, folic acid)	Minimize undesirable flavors, enable gradual nutrient release, enhance resistance to extreme temperatures and humidity, and decrease interactions between nutrients and other ingredients	Protects vitamins from degradation and enhances bioavailability	Fortified foods, supplements
Enzymes and microorganisms (lipase, invertase, *Brevebacterium linens*, *Penicillium roqueforti*, lactic acid bacteria)	Enhances storage stability in dried form, shortens ripening time, and boosts the stability of starter cultures	Increases efficacy and protects from environmental factors	Probiotic products, dairy products, fermentation processes
Sweeteners (sugars, food or artificial sugars; aspartame)	To decrease moisture absorption, enhance flowability, and extend the sweetness sensation	Maintains stability and prevents clumping or degradation	Sugar substitutes, beverages, baked goods
Colours (Anato, β-carotene, turmeric)	Encapsulated colors are more manageable and provide better solubility, enhanced stability against oxidation, and superior control over stratification compared to dry blends	Enhances visual appeal and protects colors from fading	Processed foods, confectioneries, beverages

*Source: Desai and Park, 2005

In matrix systems, the active ingredient is released through the diffusion of the base material to the surface of the coating. The active agent then dissolves between the carrier and the surrounding environment. The release rate in this method is influenced by factors such as the concentration of the active agent, the type of coating material, and the specific system design (Azevedo and Reis, 2005).

Controlled release swelling involves a process where the polymer matrix, when placed in a thermodynamically compatible medium, swells and absorbs liquid from the surrounding environment. As the matrix swells, the active ingredient within the swollen area diffuses out, leading to the controlled release of the agent (Fan and Singh, 1989).

Release of the active agent by degradation occurs when enzymes, such as proteases and lipases, break down proteins or lipids, respectively. An example of this type of release is the accelerated maturation of cheddar cheese, where the time required for maturing is reduced by 50% compared to traditional ripening methods (Rosen, 2006).

Solvent-activated release occurs when the active ingredient is released as the nutrient material comes into contact with a solvent, causing the microcapsule to swell. For instance, a microencapsulated coffee flavor is released when it comes into contact with water (Frascareli *et al*., 2012).

pH-controlled release involves the release of the active ingredient at a specific pH level. For example, microencapsulated probiotic microorganisms are designed to withstand the acidic pH of the stomach and release their contents at the alkaline pH found in the intestine (Toldra and Reig, 2011).

Temperature-sensitive release occurs when the active ingredient is released in response to changes in temperature. For example, tea and baking flavors are released based on the melting effect of the matrix, while the encapsulated cheese flavor in microwave popcorn is released when the temperature rises to 57-90°C (Park and Maga, 2006).

Pressure-activated release occurs when the active ingredient is released upon the application of pressure to the matrix. An example of this is the release of sweeteners and/or flavorings in chewing gum when it is chewed (Wong *et al.,* 2009).

In a study by Gokmen *et al.,* 2011, omega-3 fatty acids from flaxseed oil encapsulated in a high amylose corn starch coating were incorporated into bread dough and their stability during the baking process was tested. The main compounds trapped in the high amylose corn starch particles are protected against exposure to oxygen and oxidation during high temperature processing.

Curcumin is widely used in a variety of foods (oils, emulsions, confectionery, dairy products, grain products, meat and fish products, spices and sauces) as a natural colorant. Due to its carbonyl function, curcumin is very effective in converting asparagine to acrylamide. Hence, its encapsulation can reduce acrylamide formation in matrices containing asparagine and under long-term heating conditions by reducing curcumin involvement in beacon reactions (Hamzalioglu *et al.,* 2013).

Conclusions

A review of research and technology regarding the application of encapsulation of bioactive compounds for food applications is presented. The main forms of encapsulation are microencapsulation. There is great interest in the development of microcapsules loaded with polyphenols, carotenoids, fatty acids, phytosterols, probiotics, vitamins, minerals and bioactive peptides from natural sources for the food industry. The main objectives of the encapsulation strategy are to improve stability, solubility, bioavailability, sensory properties, preserve bioactive properties and microstructure, reduce hygroscopicity and increase shelf life. The most widely used polymers are gum arabic, starch and chitin, while the most commonly used encapsulation technologies are emulsion spray drying, emulsion freeze drying, complex coacervation, followed by others such as the emerging technology known as supercritical microencapsulation. More studies are needed on bioavailability for food applications and the effectiveness of bioactivity in bakery products. However, the potential of encapsulation in polymer matrices makes it a good strategy to protect bioactive compounds and expand their use in foods.

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