applied sciences

MDPI

Review

Innovative Methods of Encapsulation and Enrichment of Cereal-Based Pasta Products with Biofunctional Compounds

Weronika Bińkowska, Arkadiusz Szpicer *, Iwona Wojtasik-Kalinowska and Andrzej Półtorak

Department of Technique and Food Development, Warsaw University of Life Sciences—SGGW, 02-776 Warsaw, Poland

* Correspondence: arkadiusz_szpicer@sggw.edu.pl

Abstract: Nowadays, cognizant consumers expect products that, in addition to fulfilling a nutritional role, exhibit health-promoting properties and contribute to overall well-being. They expect an increase in the nutritional value of the staple foods that they often consume, such as pasta, through the incorporation of bioactive compounds. Due to their susceptibility to photo- and thermolability, it is necessary to protect biocompounds against external factors. A modern approach to protecting bioactive compounds is microencapsulation. The aim of this article was to present various microencapsulation methods (including spray-drying, freeze-drying, liposomes, and others) and a review of research on the use of microencapsulated bioactive compounds in pasta. The discussed literature indicates that it is possible to use microencapsulated bioactive compounds, such as fatty acids or phenolic compounds, in this product. However, further research is necessary to develop the possibility of reducing the costs of such a procedure so that the benefits for consumers are greater than the disadvantages, which are an increase in food prices. There is also little research on the use of microencapsulated probiotics, vitamins, and minerals in pasta, which also represents an opportunity for development in this aspect.

Keywords: biocompounds microencapsulation; functional ingredients; cereal product enhancement; pasta fortification; pasta biofunctionalization

check for updates

Citation: Bińkowska, W.; Szpicer, A.; Wojtasik-Kalinowska, I.; Półtorak, A. Innovative Methods of Encapsulation and Enrichment of Cereal-Based Pasta Products with Biofunctional Compounds. *Appl. Sci.* **2024**, *14*, 1442. https://doi.org/10.3390/app14041442

Academic Editors: Monica Gallo and Marco Iammarino

Received: 28 November 2023
Revised: 27 January 2024
Accepted: 7 February 2024
Published: 9 February 2024

1. Introduction

The consumption of cereal-based products is high around the world, with many countries considering them staple foods that contribute significantly to their diet's energy and nutrient intake. Consumers often choose these products due to their low price, ease of preparation and high sensory value. However, nowadays, consumers expect products that, in addition to fulfilling a nutritional role, also have health-promoting properties and improve well-being [1]. The main requirements include the use of whole grain flours, elimination of gluten, and reducing the share of artificial colors and preservatives. Moreover, there is an increasing interest in products with an enhanced content of bioactive compounds. The easiest way to obtain such products is to fortify them directly with vitamins and minerals or with products that contain a large amount of them, such as plant extracts. The greatest disadvantage in using these compounds is their thermal and photolability [2,3]. This is especially important for heat-treated products. Pasta production is based on mechanical processes such as mixing and extrusion, but also thermal processes such as drying. Each of these processes may reduce the content of bioactive compounds. Moreover, they usually have a long shelf life and storage period prior to cooking, which both also affect the content of these compounds.

To prevent the negative impact of environmental conditions on these compounds, microencapsulation technology can be used. This innovative technique involves enveloping these bioactive components in capsules the size of which ranges from 1 to 1000 µm (microcapsules) or 1 nm to 1 µm (nanocapsules), shielding them from degradation during processing and storage. The most common microencapsulation technique, being the shell/core encapsulation, involves enclosing the core substance (also referred to as an active or encapsulate) inside the outer material (matrix, shell, wall, coating, encapsulant). Other structures include multilayer complex microcapsules and cores dispersed in a continuous matrix. The matrix is a barrier separating the core from the external environment. The main advantage of this method is the possibility of using substances in various states of matter, including gases, liquids and solids [4–7]. The coating can consist of carbohydrates, proteins and fats. The most commonly used carbohydrates include starches, maltodextrin, cellulose and cyclodextrin. In the case of proteins, these are gluten, casein and gelatin. The fats most commonly used in microencapsulation are waxes, e.g., beeswax, paraffin and diacylglycerols. It is also possible to use gums such as gum arabic, guar, or carrageenan. There are many microencapsulation methods; the most commonly used are spray-drying (SD) and freeze-drying (FD). Less frequently used methods are microencapsulation by encapsulation in liposomes, coacervation or fluidized bed coating [8–10].

When incorporated into food products such as pasta, these microcapsules release their contents, ensuring the preservation of nutritional potency until consumption. The benefits of using the microencapsulation technique, apart from protecting the core substance, include the possibility of extending the shelf life of the product, controlling the release of the active substance and preventing its interactions with other food ingredients. It is also possible to use the microencapsulation method to mask the color, taste and smell of the active substance, which is particularly important when using compounds with intense aroma and color. This allows for limiting negative changes in the sensory evaluation of products by consumers [11,12].

This work presents various microencapsulation methods, highlighting their key features, benefits and challenges in their application, and the possibilities of their use in the protection of various active compounds. This review focuses on current research, published mainly in the last 5 years. It focuses specifically on articles regarding pasta, and does not include other cereal products that have been addressed in similar reviews. Instead, the analysis was expanded to include a classification of the various groups of bioactive compounds in which pasta was enriched. Therefore, examples of the use of unsaturated fatty acids, probiotics, vitamins and minerals, and bioactive compounds from vegetables and fruits in the pasta production are presented. Finally, conclusions from the presented research and future trends are discussed.

2. Methods of Encapsulation

2.1. Emulsion-Based Encapsulation and Hydrogels

Oil-in-water emulsions involve the suspension of small lipid droplets in a continuous aqueous phase. These emulsions are found extensively in applications in the food, pharmaceutical, and cosmetic industries as potential carriers for lipophilic bioactive compounds [13]. However, it is important to note that these emulsion systems can exhibit unpredictable behavior due to thermodynamic instability, leading to issues like flocculation, coalescence, creaming, and even phase separation, which can hinder their practical use [14].

Enhancing the stability of emulsions can be achieved by encapsulating the oil droplets within a three-dimensional solid matrix, such as hydrogels [15]. Polysaccharide hydrogels are commonly employed as carrier materials and have been shown to improve the stability of systems loaded with active compounds [16]. Additionally, reducing the size of emulsion droplets can enhance the migration and efficacy of bioactive substances. Nanoemulsions, characterized by low interfacial tension, offer thermodynamic stability and resistance to temperature fluctuations [17].

Hydrogels can be classified based on the type of crosslinking forces into physical and chemical hydrogels [18]. Chemical crosslinking involves the formation of covalent bonds between polymer chains through the polymerization of low-molecular-weight monomers or crosslinking of polymer precursors. Hydrogels created through chemical crosslinking exhibit remarkable stability and the ability to maintain their structure over time, with variations in structure depending on the crosslinking degree and polymer-to-reagent proportions. Common chemical crosslinking methods include the use of crosslinking agents, graft polymerization, and radiation crosslinking [19].

In contrast, hydrogels formed through physical crosslinking are generally non-toxic since no chemical reagents are involved in their preparation [20]. This makes them suitable for producing safe and eco-friendly natural hydrogels based on polymers, which are highly favored, especially in the food industry. Physical crosslinking relies on non-covalent forces to create reversible hydrogels. The strength of these non-covalent forces between polymer chains significantly influences the hydrogel's structure. By controlling factors such as pH, temperature, and polymer concentration, one can achieve the desired properties in physically crosslinked hydrogels [21]. Various physical crosslinking methods have been developed, including processes such as heating/cooling, freeze–thaw cycles, and complex coacervation, for the preparation of natural polymer-based hydrogels [22]. A diagram of the emulsion-based encapsulation method is shown in Figure 1.

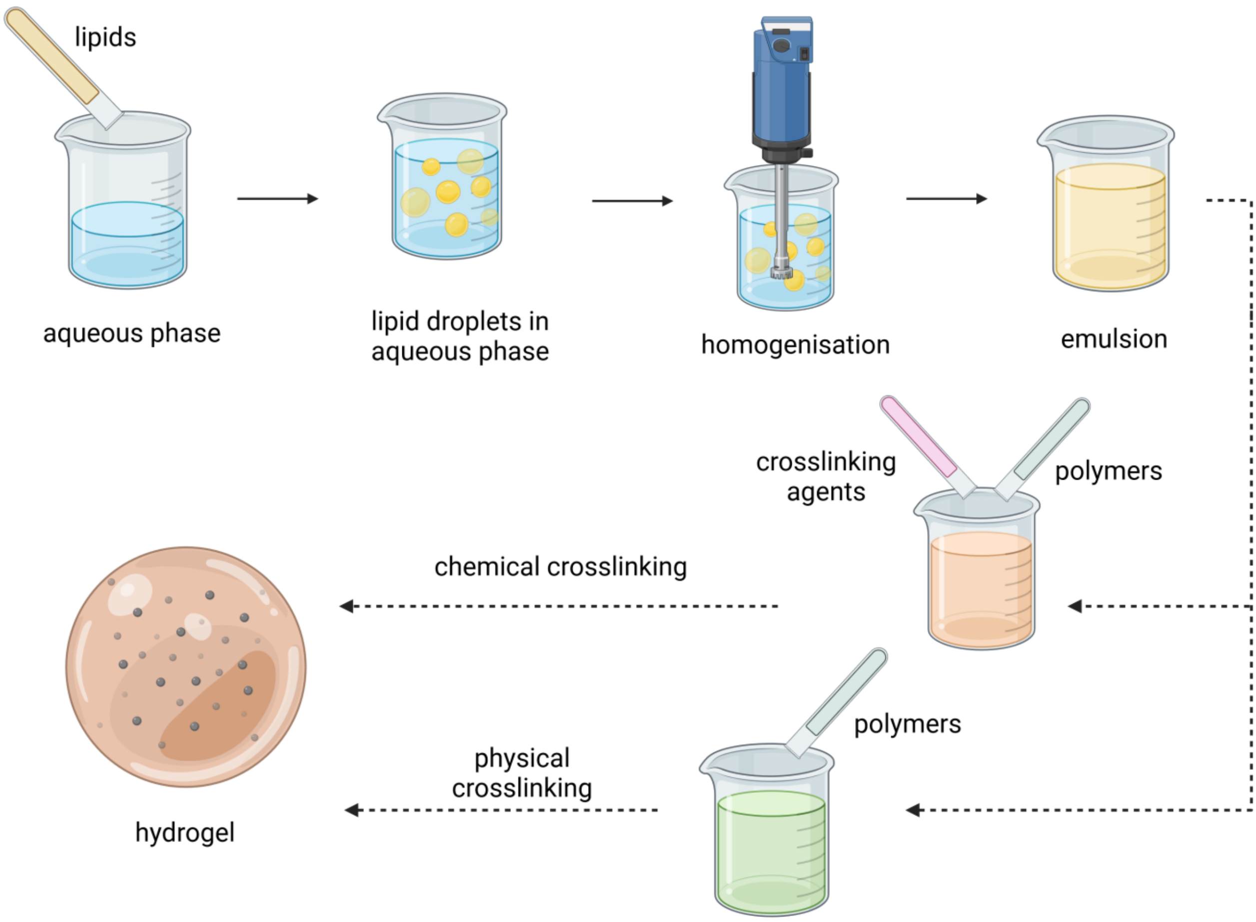

Figure 1. Emulsion-based microencapsulation (created with BioRender.com (accessed on 26 November 2023)).

2.2. Spray-Drying

One commonly used technique for microencapsulation is the SD method. This approach involves the creation of a protective shell around the core by evaporating the solvent from the solution containing the wall-forming substance. Figure 2 shows the diagram of the SD encapsulation method. SD is particularly useful for encapsulating fatty or fat-soluble compounds, including fragrance oils, as well as aromatic substances composed of highly volatile aldehydes, ketones, alcohols, esters, and ethers [23,24]. This method is also used to microencapsulate bioactive and health-promoting compounds such as polyphenols, flavonoids, etc. [25,26]. Typically, polysaccharides such as modified starch or gum arabic are used as coating materials in the SD process. An essential factor affecting the quality of the capsules is the air temperature. It is recommended that the inlet temperature of the dryer should range from 160 to 210 °C, while the outlet temperature should be maintained at 80 to 90 °C. Due to the use of high temperatures, this method cannot be used for the microencapsulation of highly thermolabile materials. Substances that need to be encapsulated using other methods include lactic acid bacteria, proteins, or unsaturated fatty acids [27]. Spray solidification (spray chilling) is more widely used in the microencapsulation of thermally labile substances [28]. This method involves suspending core particles in a molten wall material with a low melting point (32–42 °C) and then spraying this mixture in cold air, water, solvent, or liquid nitrogen, which quickly hardens the wall [4]. Thanks to the complexation with polyethylene glycol, the SD of hydrophobic biomaterials is possible, and chitosan has been proven to be useful in creating systems for the controlled release of active substances in the body [29]. Microcapsules obtained by SD are spherical, their size range varies from 10 μm to 2 mm and depends on the process parameters and encapsulated materials [30].

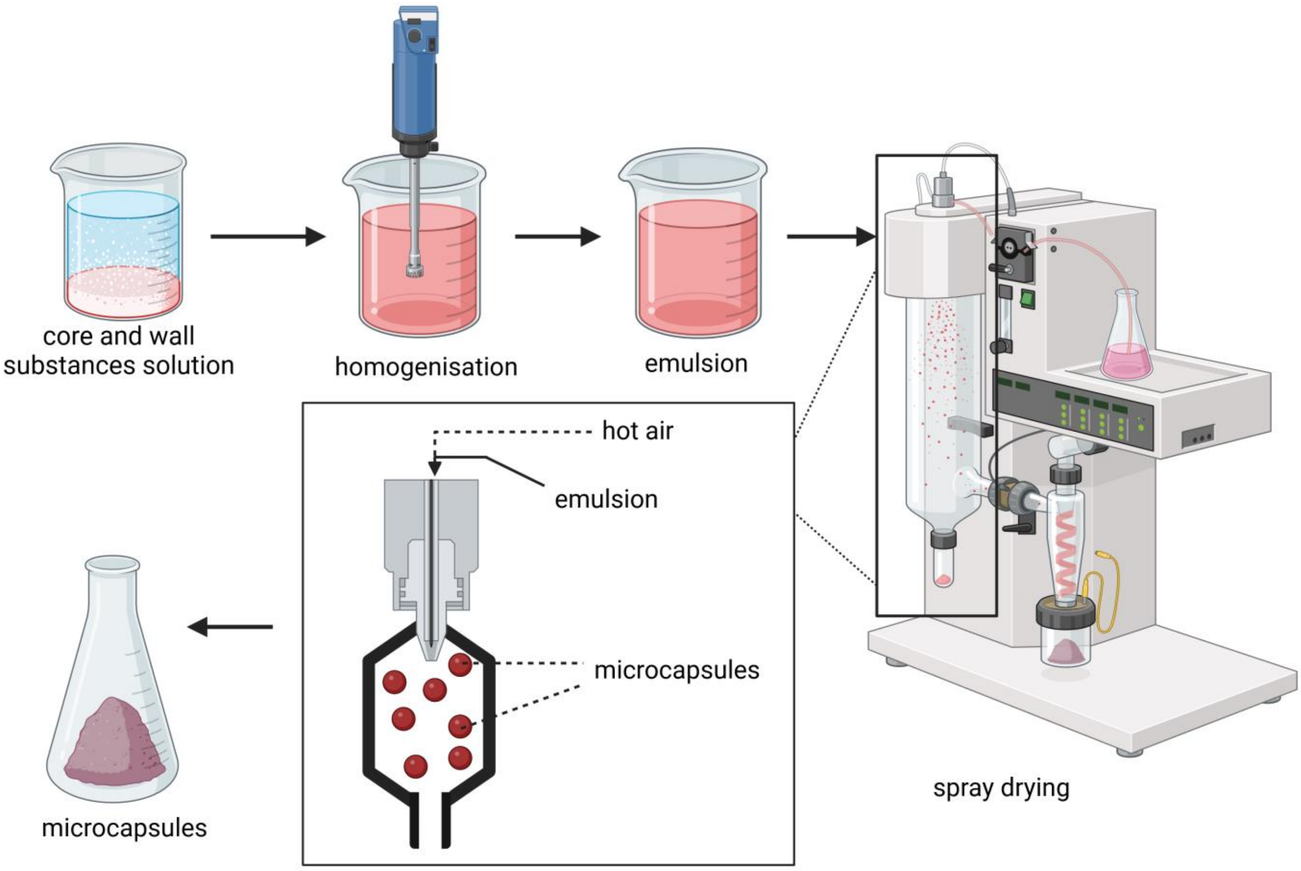

Figure 2. Spray-drying encapsulation (created with BioRender.com (accessed on 26 November 2023)).

2.3. Freeze-Drying

Freeze-drying encapsulation requires creating a solution comprising the desired compound and the encapsulation materials, which is subsequently transformed into microcapsules using the freeze-drying method [31]. Freeze-drying is used for the microencapsulation of natural flavors, extracts, lipids, probiotics, and various bioactive substances. While freeze-drying is a straightforward technique well suited for encapsulating aromatic compounds, it does require a lengthy dehydration period [32,33]. The preservation of volatile compounds during freeze-drying is contingent on the chemical characteristics of the system and the process parameters [34].

Prior to the commencement of microencapsulation, a solution is prepared, and frequently, one of its constituents is starch. Native starch is inherently hydrophilic, but through the esterification of starch's hydroxyl groups with a hydrophobic substituent, starch transforms into an amphiphilic substance. The resulting derivative of starch in this process is referred to as octenyl succinic anhydride (n-OSA) [35].

The microencapsulation process through freeze-drying takes place under low-temperature and low-pressure conditions. These specific conditions ensure a high degree of preservation for thermolabile compounds that would degrade or undergo alterations in alternative microencapsulation methods. Substances such as unsaturated fatty acids can be successfully microencapsulated using this method [36]. In addition, some types of molecules, such as coacervates or complexes, benefit from the use of FD for isolation [6]. FD is a method suitable for volatile compounds because it does not require the use of high temperatures, which could cause the thermal decomposition of compounds. It allows for the preservation of the original properties in terms of the color, aroma, taste, texture, or biological activity. It does, however, involve the possibility of losses during production and an increase in the release time due to the formation of a porous wall between the compounds and the surroundings. Despite its numerous advantages, freeze-drying is consistently regarded as the most costly method for producing dehydrated products. This is due to the high energy consumption associated with the necessary freezing of the product, followed by a long primary drying process when sublimation occurs, and a secondary drying process when evaporation occurs. It is also bound up with the long duration of each of these processes [37]. A diagram of the FD encapsulation method is shown in Figure 3.

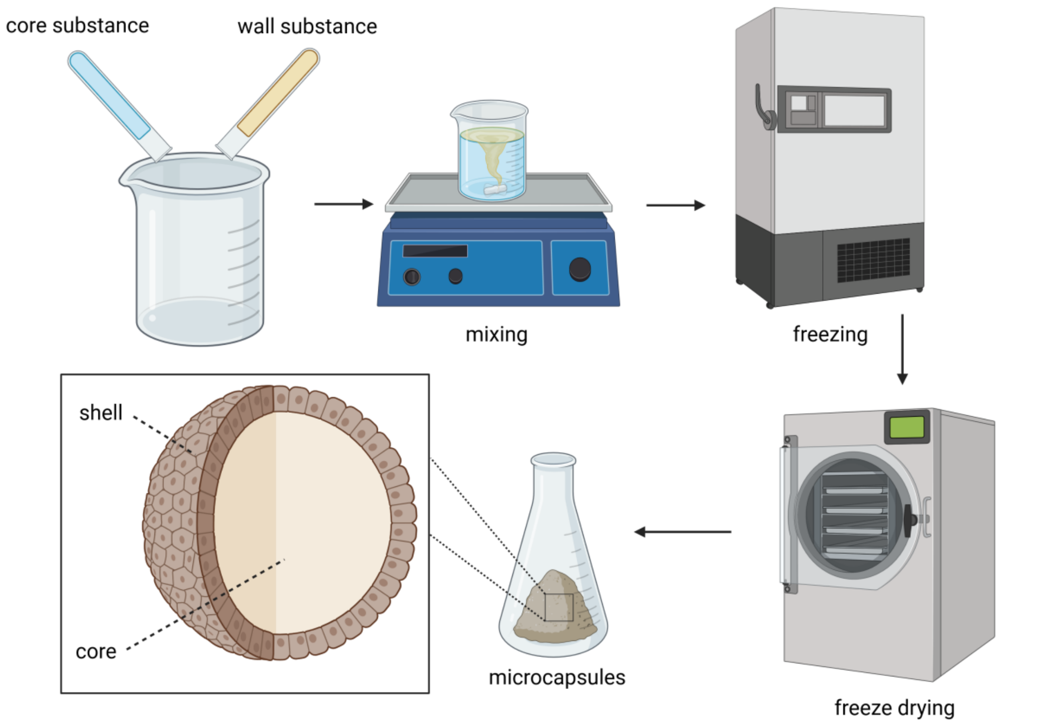

Figure 3. Freeze-drying encapsulation (created with BioRender.com (accessed on 26 November 2023)).

2.4. Liposomes

Liposomes consist of a single or multiple bilayer membranes composed of phospholipids that have a hydrophilic head and hydrophobic tail groups. The hydrophilic heads are in contact with the internal aqueous layer and the external environment, while the tails form a bilayer. Thanks to this, it is possible to encapsulate both water- and fat-soluble compounds in liposomes. However, the entrapment of compounds soluble in both media is not possible. A particular advantage of this technology is the possibility of the simultaneous encapsulation of lipophilic compounds (in the layer between the tails) and hydrophilic compounds (inside the liposome). This allows for the use of compounds with different structures in one capsule, which may have a synergistic effect [38,39]. A diagram of the liposomal encapsulation method is shown in Figure 4.

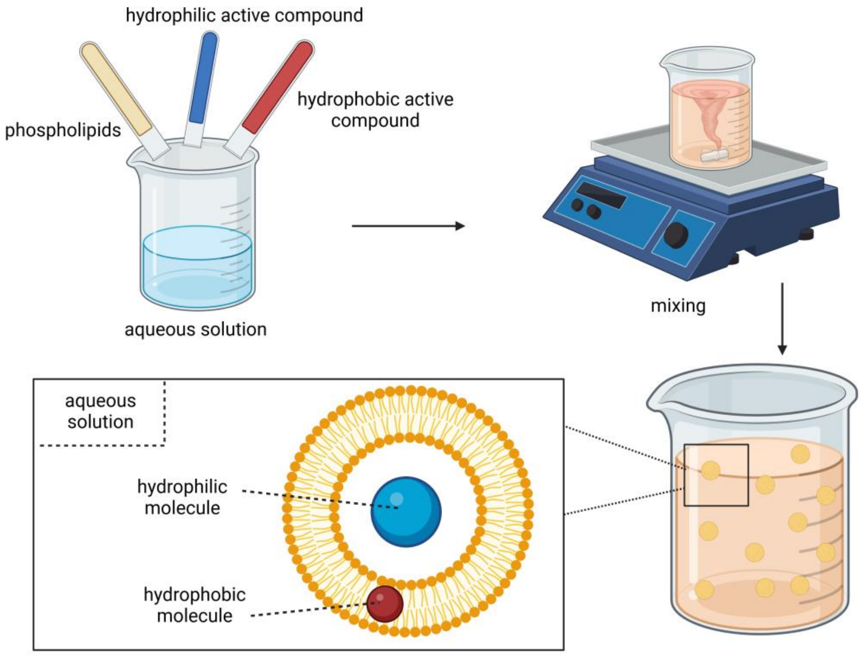

Figure 4. Liposomal encapsulation (created with BioRender.com (accessed on 26 November 2023)).

Liposomes are created by mixing phospholipids with other compounds in an aqueous solution. The most commonly used phospholipid is lecithin obtained from soy or egg yolk, but fatty acids can also form liposomes. One method of creating liposomes is to incorporate hydrophilic components into the interior of the liposome, and hydrophobic components into the lipid bilayer during liposome formation. Another approach is to encapsulate compounds into existing liposomes. This involves an additional driving force, often obtained by using ammonium sulfate and calcium acetate. This method is used when there is a higher compound-to-lipids ratio. The isolation of liposomes involves the use of various techniques including microfluidization. Often, organic solvents such as ethanol, methanol, or hexane are also used to dissolve hydrophilic or hydrophobic substances. The size of liposomes ranges from several nanometers to micrometers. The size and the structure are influenced by the composition, production method, and environmental conditions. To obtain smaller liposomes with a uniform, typical spherical structure, it is necessary to use energy; for example, through ultrasonication or high-pressure homogenization [40–43].

In the food sector, the liposome encapsulation method is used for flavorings, amino acids, essential oils, vitamins, minerals, antioxidant compounds, preservatives, enzymes, and probiotics [43,44].

The main disadvantages of this technique include its low efficiency, a highly acidic pH, the use of organic solvents, and the costs associated with the use of sonification, homogenization, or pressure forces [43].

2.5. Selected Other Methods

Less commonly employed microencapsulation methods in food technology include, among others, coacervation, ionic gelation, fluidized bed coating, solvent evaporation, the rapid expansion of supercritical solutions, and cyclodextrin-based encapsulation [45,46].

Coacervation is based on the chemical interactions of colloids. This method involves the formation of a complex between oppositely charged core and matrix molecules in an aqueous solution. Coacervation may be simple or complex. Simple coacervation requires the use of one polymer and a strong hydrophobic compound, while the complex one requires the use of two or more polymers to enclose the core in the capsule [7,44,47].

Fluidized bed coating is based on the fluidization. It involves the formation of a dynamic suspension of small solid particles in a gas stream moving from bottom to top. It takes place in a vertical column, at the bottom of which powdered core material is placed. Through a perforated bottom, a stream of compressed gas is passed upwards. The polymer solution constituting of the coating is administered from the top or bottom of the column. When floating under the influence of gas, the core particles are stuck to the wall particles. At the same time, the drying process takes place [6,48,49].

Electrostatic SD differs from the conventional methods by using an electrostatic charge. This results in the solvent molecule (water) having the highest dipole moment and the bioactive molecule having the lowest. As a result, the water molecules move more rapidly to the outer surface of the droplet for evaporation. This allows one to reduce the drying temperature up to 90 °C, which has a positive effect on reducing the degradation of thermolabile compounds [50,51].

Cyclodextrins are macrocyclic oligosaccharides consisting of six, seven, or eight glucopyranose units produced as a result of the enzymatic modification of starch. They can form walls, which allows for the creation of small cavities in which other ingredients may be located. In this method, core compounds form non-covalent bonds with cyclodextrins, forming microcapsules [52].

3. Application of Microencapsulated Ingredients in Pasta Products

3.1. Oils and Fatty Acids

The microencapsulation of oils represents a significant technology in various fields such as pharmaceuticals, the food industry, and the cosmetic industry. One of the key advantages of this process is the enhancement of the stability and durability of oils, shielding them from factors like light, oxygen, or humidity, which allows for the preservation of their quality and effectiveness over an extended period [38]. Additionally, microcapsules enable the controlled release of active substances [53]. The microencapsulation of oils also holds considerable importance in the context of reducing undesirable odors and flavors, especially in the case of oils containing unsaturated fatty acids. This process allows for the effective masking of characteristic aromas that may be unacceptable to consumers or patients. Furthermore, microcapsules can protect unsaturated fatty acids from oxidation, which is crucial due to their susceptibility to this process. Also, microencapsulation can increase the thermal stability of oils, meaning they can withstand higher temperatures during the food production process, leading to less of a loss of quality and nutritional value [54]. These microcapsules are variously shaped, varying in the number of cores and sizes, and can be produced using a variety of techniques such as jet cutting, sputtering, SD, dispersion, and microfluidics [55]. Polymers are often used for the microencapsulation of oils, with alginates being popular due to their gelling ability, biocompatibility, and low toxicity. Alginates form a hydrogel in the presence of calcium ions, which allows the oil to be protected inside the microcapsule. Oil microcapsules can be produced by dispersing an oil emulsion and a calcium alginate solution [56]. The release of calcium from the emulsion leads to the gelation of alginate around the oil droplets, forming microcapsules. A new method of producing microcapsules based on the technique of dispersing the reverse W/O gelation of an emulsion in an alginate solution allows one to obtain microcapsules of different diameters depending on the mixing speed of the bath with alginate. Microcapsules with a core–shell alginate structure, produced using the reverse gelation dispersion technique, exhibit interesting properties that are suitable for applications where active substances need to be retained for a long time or in the case of volatile compounds [23,24]. Table 1 shows the results of the latest research on enriching pasta with microcapsules containing vegetable and animal oils.

Table 1. Application of encapsulated plant and animal oils in pasta.

Core Material	Wall Material	Encapsulation Method	Results	Reference
Chia seed oil	Soy protein isolate	FD	• The microencapsulation process did not negatively affect its FA quality. • The n − 3 enriched pasta did not show significant differences in cooking time or CL values, indicating that the quality of the cooked pasta was good. • WA was lower in the omega-3 enriched pasta, suggesting that the presence of these FAs may affect water distribution during cooking. • Raw pasta enriched with chia seed oil had a lower shear force compared to the control pasta. • The texture of the cooked pasta was not negatively affected by the addition of FA.	[57]
LC n − 3 PUFA (marine oil)	Cornstarch-coated matrix of fish gelatin and sucrose	No data. Marketable product was used—ROPUFA 10 n − 3 food powder (Roche, Basel, Switzerland)	• ROPUFA powder contained significant levels of EPA (19%) and DHA (26%) along with other fatty acids. • The premix formulations had varying levels of LC n − 3 PUFA, reflecting the addition of an integrator. • The fatty acid composition of spaghetti closely resembled that of the premix, indicating that processing and the diameter did not significantly affect fatty acid composition. • The n − 6/n − 3 ratio in the fortified spaghetti significantly decreased, in line with nutritional recommendations for a lower n − 6/n − 3 ratio. • Fortified spaghetti provided 10–31% of the recommended daily intake of LC n − 3 PUFA per serving (80 g). • Fortified spaghetti was well accepted in sensory analysis, with no significant differences in color, taste, and overall acceptability observed up to 1.2% integrator content. • Spaghetti with a higher integrator content had some perceptible differences in aftertaste and flavor. • Microencapsulation technology helped mask fishy flavors and protect against oxidation.	[58]

Table 1. *Cont.*

Core Material	Wall Material	Encapsulation Method	Results	Reference
LC n − 3 PUFA (marine oil)	Cornstarch-coated matrix of fish gelatin and sucrose	No data. Marketable product was used—ROPUFA 10 n − 3 food powder (Roche, Basel, Switzerland)	• Enriching spaghetti pasta with LC n − 3 PUFA such as EPA and DHA through microencapsulation effectively increased the fat content. • LC n − 3 PUFA increased significantly in functional spaghetti to 55.5 mg/100 g for EPA and 80.8 mg/100 g for DHA, contributing to recommended LC n − 3 PUFA intake. • Lipid oxidation during storage was investigated, with a focus on PV and OFA levels. • Light exposure significantly accelerated lipid peroxidation compared to the accelerated shelf life conditions. • In light-exposed spaghetti, both control and enriched samples showed a doubling of PV after three months, with a subsequent five-fold increase by the end of six months. • No significant difference was observed between the two types of spaghetti after 10 months of light exposure. • OFA levels increased at a slower rate in enriched spaghetti compared to control spaghetti under light exposure. • Microencapsulation protected against secondary oxidation products. • Microencapsulation effectively protected LC n − 3 PUFA from oxidation.	[59]
LC n − 3 PUFA	Modified starch, sucrose, sodium ascorbate, silicon dioxide	No data. Marketable product was used—ROPUFA 10 n − 3 food powder (Roche, Basel, Switzerland)	• Drying at different temperatures significantly influenced the stability of LC n − 3 PUFA in the spaghetti. • Drying at 90 °C resulted in a decrease in n − 3 stability in the fortified spaghetti compared to drying at 55 °C and 75 °C. • The spaghetti dried at 75 °C showed the highest retention of long-chain omega-3 fatty acids after cooking.	[60]
Fish oil	Sodium alginate, Carrageenan along with gelatin and maltodextrin	SD α-cyclodextrin	• Fish oil, rich in omega-3 fatty acids, is prone to oxidation, limiting its use in food. Microencapsulation offers a solution for protection. • Sodium alginate, with gelatin and maltodextrin, was used to microencapsulate fish oil through SD (1:4 ratio). • The microencapsulated fish oil had high encapsulation efficiency, good flow properties, and spherical particles ranging from 1.76 µm to 19.7 µm. • Microencapsulates with sodium alginate showed superior oxidative stability compared to carrageenan. Sensory analysis indicated that noodles fortified with up to 2% fish oil encapsulates were acceptable without affecting taste.	[61]

Table 1. *Cont.*

Core Material	Wall Material	Encapsulation Method	Results	Reference
Pumpkin oil	α-cyclodextrin	FD	• Adding SC-CO_2 extracted pumpkin oil, either free or encapsulated in α-CDs, to semolina improved the levels of phytosterols, squalene, carotenoids, tocochromanols, and unsaturated fatty acids in spaghetti, providing a significant portion of the recommended daily intake for vitamins A and E, along with increased lipophilic antioxidant capacity. • Complexation of pumpkin oil with α-CDs slightly increased the fiber content in the pasta. • This complexation also enhanced the stability of certain bioactive components during pasta production and improved the firmness of cooked spaghetti compared to the control sample. Despite some negative effects on taste, firmness, bulkiness, and stickiness, the overall sensory evaluation was satisfactory. • Although the production cost of this pasta is higher than traditional options, it is believed that it could appeal to consumers due to its well-balanced combination of health benefits and taste, making it an innovative product to address specific nutritional or health-related needs.	[62]

3.2. Fruit and Vegetable Biocompounds

Non-essential bioactive compounds from vegetable and fruit include phenolic compounds, carotenoids, phytosterols, and essential oils. They have antioxidant, antimicrobial, anti-inflammatory, and anti-carcinogenic properties [63]. Their health-promoting effects are also associated with a positive impact on the body's microbiota and reducing the risk of diseases and conditions such as stroke and other heart diseases, diabetes, inflammation, and neurodegenerative diseases [64,65]. Their properties and high availability make them frequently used in food products. To fortify food products, compounds derived from fresh fruit and vegetables, and likewise, their by-products, may be used [66]. However, maintaining their properties is difficult due to their sensitivity to light and temperature. Microencapsulation allows for the ability to maintain their high content and the health-promoting properties of enriched products. The main methods of the microencapsulation of bioactive compounds from vegetables and fruits include SD and FD. The substances mostly used as a matrix are whey protein, maltodextrin, modified starch, gum arabic, and xanthan gum.

Studies have shown that microencapsulation does not completely inhibit the reduction in the content of phenolic compounds during the storage of pasta enriched with microcapsules, but it leads to maintaining the content at a higher level than in the case of enrichment with free extract. Moreover, pasta with a microencapsulated extract has a higher sensory acceptability than pasta with the addition of a free extract [67]. Another important feature is the increased thermal stability of products containing microencapsulated bioactive compounds [68]. This was also proven in the study in ref. [69], where 1% of the additional content of microencapsulated chlorophyll in pasta caused an increase in the denaturation peak temperature by 29 °C. Research also shows that the use of microencapsulated bioactive compounds improves the textural properties of pasta and reduces cooking losses, but may extend the cooking time, which may be caused by changes in the surface morphology of noodles [69,70]. Table 2 presents the latest research on the use of microencapsulated compounds from fruits and vegetables in pasta.

Table 2. Application of encapsulated fruit and vegetable compounds in pasta.

Core Material	Wall Material	Encapsulation Method	Results	Reference
Soybean molasses	Hi-maize®	SD	• Losses of phenolic compounds occurred in both pasta with free extract and microencapsulated extract. • In cooked pasta containing both free extract and microcapsules, the level of polyphenols after 14 days of storage was 25% of the initial value, and in raw pasta 15% of the initial value remained after storage for 21 days. • The use of microcapsules did not affect the microbiological profile, pH, water activity or color of the product. • Pasta containing microcapsules was characterized by high sensory acceptability, similar to that of the control pasta, but free extract pasta was less acceptable.	[67]
Carrot waste extract	Whey protein (FD), whey protein/inulin (SD)	FD, SD	• The use of microcapsules with carrot waste extract in oil resulted in a product with an increased content of carotenoids and tocols. • Enrichment resulted in an increase in the stability of bioactive compounds and an extension of the cooking time as well as a reduction in cooking loss, weight increase index, water absorption, and stickiness of the pasta surface. • Pasta with 10% microcapsules had a high sensory acceptability, similar to the control. • One serving of the product with 10% enrichment contained 15% and 17% of vitamin A equivalent as well as 23% and 25% of vitamin e recommended daily allowance (FD and SD, respectively).	[70]
Chlorophyll	Gum arabic/whey protein isolate	FD	• The use of microencapsulated chlorophyll resulted in an improvement in the cooking quality of pasta. • Texture properties (hardness, resilience, and chewiness) were also improved, but cohesiveness was not changed. • As the addition content of microcapsules increased, the denaturation peak temperature increased. • Pasta with 0.5% microencapsulated chlorophyll had the highest sensory acceptability of all tested, including the control.	[69]

Table 2. *Cont.*

Core Material	Wall Material	Encapsulation Method	Results	Reference
Spirulina	Sodium alginate/calcium chloride	SD	• The use of microencapsulation technology resulted in a reduction in the loss of antioxidant potential by 38% compared to free spirulina. • Pasta with the addition of microencapsulated and free extract showed lower water activity than the control, which may be due to lyophilization, which made the ingredients dryer compared to the control, but also due to the use of alginate and calcium chloride, which improve the water binding ability. • Pasta with microcapsules showed a lower intensity of green color than pasta with free extract. • Cooking time did not vary regardless of the type of pasta. • The use of microcapsules and free extract had no effect on cooking loss and swelling index of pasta. • Both pasta with microcapsules and free extract were characterized by similar acceptability as the control, which proves that the greenish color and characteristic smell no longer have a negative impact on consumer acceptability.	[71]
Azolla	Sodium alginate/calcium chloride	FD	• Pasta containing microencapsulated Azolla powder had lower moisture and water activity than control pasta. • Pasta with the addition of microcapsules had a higher green hue value (a*) than the control pasta, but it was lower than that of pasta with the addition of free Azolla powder. • Both the use of microencapsulated and free powder had no significant effect on the cooking loss and swelling index of pasta. • Water absorption values of both the pasta with microparticles and with free powder were lower than the control. • Pasta with microcapsules had higher firmness and hardness values compared to the control. • Macaroni with microcapsules had higher sensory ratings than the control in all attributes except taste, which proves that the use of microencapsulation can improve the consumers' acceptance of the product.	[72]

Table 2. *Cont.*

Core Material	Wall Material	Encapsulation Method	Results	Reference
Carrot waste extract	Whey protein (FD), whey protein/inulin (SD)	FD, SD	• Pasta with microcapsules had higher protein, fat, and ash content, as well as lower carbohydrate and moisture content. • Pasta without microcapsules had the lowest cooking weight whereas pasta with SD microcapsules had the highest. The increase in cooking weight of pasta with microcapsules was caused by the content of whey protein, which contains polar amino acids that have a high water-binding capacity. Additionally, the SD microcapsules contained inulin, which is highly hydrophilic and so increases the value more. • The use of microcapsules resulted in an increase in the swelling index. • The change in color caused by microparticles was visible to observers, as evidenced by the high ΔE values. The ΔE value increased with an increase in the proportion of microcapsules in the product, but was also higher in the case of SD than FD. • Changes in texture depended on the microencapsulation technology and the level of enhancement. For all enriched products, there was an increase in hardness. Samples with a high level of enrichment (20%), regardless of the encapsulation method, had worse springiness and cohesiveness. Gumminess and chewiness were increased in pasta with FD and decreased with SD microcapsules.	[73]
Ferulic acid from tomato pomace	Whey protein isolate (1:1 and 1.5:1 wall-to-core ratio)	SD (105 °C and 90 °C drying)	• The lowest cooking loss was with pasta that had a 1.5:1 wall-to-core ratio microcapsules dried at 90 °C. Pasta with 1:1 ratio dried at both temperatures had a similar cooking loss, which was higher than the 1.5:1 ratio and the control. • 1.5:1 wall-to-core ratio dried at 90 °C microcapsules pasta exhibited the highest antioxidant activity, whereas 1:1 had similar values as pasta with free extract. • Pasta with microcapsules had the highest structure retention compared with the control and free extract pasta. • 1.5:1 dried at 90 °C microcapsules pasta had better sensory characteristics (appearance, mouthfeel, strand quality, overall acceptance) in comparison with all other pasta. 1:1, 90 °C pasta ranked below the control.	[74]

3.3. Probiotic Bacteria and Other Microorganisms

Over recent years, interest in preparations containing strains of probiotic bacteria has increased significantly. So far, many studies have been carried out and their positive impact on many diseases and the human body has been confirmed [75]. To realize the health benefits, probiotics should exhibit viability and activity in both the product matrix and the host organism [34]. Moreover, it is important that probiotics are able to break down the natural barriers of the human body. Consequently, the selection of probiotic microencapsulation methods is very important. Unfortunately, some technics, such as SD, inflict thermal stress on probiotic cells. Damage to the cell wall, cytoplasmic membrane, ribosome, and DNA during the heating process may be the main cause of loss of viability. Therefore, FD, spray coagulation, fluidized bed coating, extrusion, coacervation, and the electrostatic method are useful in probiotic bacteria microencapsulation [76]. Thanks to microencapsulation, food products fortified in probiotics can be stored, for example, at room temperature. Additionally, some strains may be released from the microcapsules in appropriate parts of the digestive tract [77]. For example, many strains of *Bifidobacterium* and *Lactobacillus* lose the ability to survive the harsh conditions of the acidity and bile concentration of the human gastric environment [78]. Using an appropriate wall material to envelop probiotic cells aids in maintaining the viability of probiotics throughout the industrial manufacturing process as they pass through the gastrointestinal system [76]. Apart from the strains mentioned above, the food industry also uses probiotics microcapsules derived from *Lactococcus*, *Enterococcus* (such as *Ent*. *faecalis* and *Ent*. *faecium*), various yeast strains (like *Saccharomyces boulardii* and *Saccharomyces cerevisiae*), and fungi (such as *Aspergillus oryzae*) [79]. Table 3 presents the results of the latest research on the use of microencapsulated probiotics in pasta production.

Table 3. Application of encapsulated probiotic bacteria in pasta.

Core Material	Wall Material	Encapsulation Method	Results	Reference
Bacillus clausii	Alginate	Extrusion	• The noodle dough contained a significant number of *B. clausii* probiotic microorganisms, ensuring their survival in the gastrointestinal system. • The addition of probiotics turned the noodles into functional food products. • Probiotic-enriched noodles aimed to improve probiotic resistance in the digestive system, potentially offering health benefits to consumers.	[80]
Lactobacillus plantarum (MTCC 5422)	FOS, DWPI, WPI, and their mixtures	FD	• In fresh noodles, both before and after cooking, a high probiotic viability of 93.63% and 62.42% was achieved for encapsulated L. plantarum cells, respectively. • In dried noodles, 80.29% (RTD) and 64.74% (HTD) of encapsulated cells remained viable. However, after cooking the dried noodles, there was a complete loss of cell viability. • Fresh noodles serve as a suitable carrier system for delivering viable probiotic cells.	[81]

3.4. Vitamins and Minerals

Vitamins are defined as a group of organic chemical compounds with various structures that are necessary for the proper functioning of an organism. They are exogenous, which means that they cannot be synthesized by the human body or their synthesis is insufficient. Therefore, they must be supplied through food. Minerals comprise a group of compounds that include macro- and microelements. Macroelements are present in the body in larger amounts and serve as building blocks for the body's tissues. These include carbon, nitrogen, and calcium. Microelements exist in the body in smaller amounts, but they are necessary for the proper functioning of the organism due to their role in the regulation of cellular processes. Micronutrients include iron, manganese, iodine, copper, zinc, and fluorine [82].

The most frequently used methods of creating microcapsules of vitamins and minerals include SD and spray freezing. As a capsule matrix, biopolymers such as modified starch, pectin, or gum arabic are most often used [83,84].

One of the most important vitamins recommended for women of all ages worldwide is vitamin B9 in the form of folic acid. The aim of the study in ref. [85] was to evaluate the characteristics of microcapsules containing folic acid, prepared using various biopolymers. It was noticed that capsules made using modified starch formed more irregular shapes, while capsules made of other substances had a more regular shape. It was also found that there were differences in the release time of the compounds. If a slower release is necessary, the use of sodium alginate or pectin is most beneficial, and for a faster release, it is best to use gum arabic, modified starch, or chitosan. This study indicated that there is potential to use biopolymers in the making of microcapsules containing thermo- and photolabile compounds in order to enhance various food products. Table 4 presents an overview of studies on pasta in which microencapsulated vitamins and minerals were used.

Table 4. Application of encapsulated probiotic vitamins and minerals in pasta.

Core Material	Wall Material	Encapsulation Method	Results	Reference
L-5-methyltetrahydro-folate (L-5-MTHF)	Modified starch	SD	• The use of microencapsulation technology improved the ability to uniformly enrich the flour to achieve the expected fortification levels. • Pasta with microcapsules retained 80% of the l-5-MTHF content after preparation and 72% after cooking, while for pasta with free l-5-MTHF, it was 70% and 30%, respectively. • In the case of the frying of egg noodles, losses were greatest in the case of free l-5-MTHF pasta. No significant differences in losses were shown for l-5-MTHF encapsulated and folic acid noodles in fresh, boiled, and fried egg noodles. • Encapsulation of l-5-MTHF with sodium ascorbate caused greater stabilization during processing and cooking.	[86]
Folic acid	Pectin/sodium alginate/sodium chloride/chitosan (GP), gelatin/gum Arabic/chitin (CC), pectin/sodium alginate (SD)	Gel particle encapsulation (GP), coacervation (CC), SD	• GP capsules were slightly soluble in acid and water-insoluble, CC capsules were water-soluble, and SD microcapsules had the highest acid solubility and were water-insoluble. Considering this, SD microencapsulation is the most suitable for vermicelli enhancement because it prevents folic acid losses during processing. • SD microcapsules color-blended better with rice vermicelli than the other two techniques. It also showed a slightly yellow color which improved the sensory acceptance of the product. • Microencapsulation reduced folic acid losses during all steps of mechanical and thermal processing, compared to the use of free folic acid. • Microencapsulated folic acid did not affect the sensory acceptance of rice vermicelli.	[87]

4. Conclusions and Future Trends

Due to the high consumption of cereal products, including pasta, the requirements regarding their quality and nutritional value are constantly increasing. Consumer awareness regarding food and nutrition is also currently increasing. They expect functional products that, in addition to providing nutritional value, have a health-promoting effect and improve well-being. These functions are fulfilled by fortified products, i.e., enriched with various nutrients usually absent in them or present in small amounts. Examples include plant drinks fortified with vitamin D and calcium or cereal products fortified with iron. Such products also include pasta enriched with bioactive compounds, such as polyunsaturated fatty acids, probiotics, phenolic compounds, vitamins, and minerals. The direct application of these compounds is hampered by their thermal and photolability. In order to protect these compounds against external factors, it is possible to use microencapsulation technology. Furthermore, this technology also allows for the regulation of the release of compounds during storage and neutralize their potentially negative impact on the sensory quality of products. Thanks to the use of microencapsulation, it is possible to obtain functional products with a high content of active ingredients. Compared to the direct application of these compounds, the use of microencapsulation technology causes fewer changes in the texture, color, or sensory evaluation and the acceptance of products by consumers. In this case, a small change in the physical characteristics of the products is accepted by consumers, since the benefits of increased nutritional value are greater than the disadvantages caused by any non-significant change in the characteristics of the product.

The presented research indicates that it is possible to use microencapsulated bioactive compounds in the production of pasta. However, it should be emphasized that there are still few reports and further research should be conducted on the use of compounds such as vitamins and minerals or probiotics, while the number of studies on the use of fatty acids and compounds from vegetables and fruits is greater. Currently, the introduction of microencapsulation technology to the industry is difficult due to the high cost of the equipment necessary to carry out this process. This increases the production costs of food products and, consequently, their prices, which may negatively affect their perception by consumers. On the other hand, the use of this technology is associated with many benefits, such as the protection of the health-promoting and anti-oxidative abilities of active compounds. Therefore, it is necessary to develop methods that allow the benefits of this technology to outweigh the costs. For this reason, further research is necessary to enhance the applicability of microencapsulation technology for bioactive compounds and their utilization in pasta production.

Author Contributions: Conceptualization, W.B.; methodology, W.B.; investigation, W.B.; resources, W.B.; data curation, W.B.; writing—original draft preparation, W.B. and A.S.; writing—review and editing, W.B., A.S. and I.W.-K.; visualization, W.B.; supervision, A.S. and A.P.; project administration, W.B.; funding acquisition, A.S. and I.W.-K. All authors have read and agreed to the published version of the manuscript.

Funding: Research financed by Polish Ministry of Science and Higher Education within funds of Faculty of Human Nutrition and Consumer Sciences, Warsaw University of Life Sciences (WULS), for scientific research.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

Biological, chemical, and microbiological

AI	Acid index
CL	Cooking loss
DHA	Docosahexaenoic acid (C22:6 n − 3)
DWPI	Denatured whey protein isolate
EPA	Eicosapentaenoic acid (C20:5 n − 3)
FA	Fatty acids
FOS	Fructo oligosaccharide
HPV	Hydroperoxide value
HTD	High-temperature dried (55 °C)
K232	Conjugated dienes
K270	Conjugated trienes
L-5-MTHF	L-5-methyltetrahydro-folate
LC n − 3 PUFA	Long-chain omega-3 polyunsaturated fatty acids
n − 3	Omega-3 fatty acids
n-OSA	Octenyl succinic anhydride
OFA	Oxygenated fatty acid
OSI	Oxidative stability index
PV	Peroxide value
RTD	Room-temperature dried (28 °C)
SC-CO_2	Supercritical carbon dioxide
SPI	Soy protein isolate
WA	Water absorption
WPI	Whey protein isolate

Instrumental techniques

CC	Coacervation
FD	Freeze-drying
GP	Gel particle encapsulation
SD	Spray-drying

References

1. Contor, L. Functional Food Science in Europe. *Nutr. Metab. Cardiovasc. Dis.* **2001**, *11*, 20–23.
2. Raczyk, M.; Kruszewski, B.; Zachariasz, E. Effect of Tomato, Beetroot and Carrot Juice Addition on Physicochemical, Antioxidant and Texture Properties of Wheat Bread. *Antioxidants* **2022**, *11*, 2178. [CrossRef]
3. Tolve, R.; Simonato, B.; Rainero, G.; Bianchi, F.; Rizzi, C.; Cervini, M.; Giuberti, G. Wheat Bread Fortification by Grape Pomace Powder: Nutritional, Technological, Antioxidant, and Sensory Properties. *Foods* **2021**, *10*, 75. [CrossRef]
4. Choudhury, N.; Meghwal, M.; Das, K. Microencapsulation: An Overview on Concepts, Methods, Properties and Applications in Foods. *Food Front.* **2021**, *2*, 426–442. [CrossRef]
5. Figueiredo, J.A.; Silva, C.R.P.; Oliveira, M.F.S.; Norcino, L.B.; Campelo, P.H.; Botrel, D.A.; Borges, S.V. Microencapsulation by Spray Chilling in the Food Industry: Opportunities, Challenges, and Innovations. *Trends Food Sci. Technol.* **2022**, *120*, 274–287. [CrossRef] [PubMed]
6. Timilsena, Y.P.; Haque, M.A.; Adhikari, B. Encapsulation in the Food Industry: A Brief Historical Overview to Recent Developments. *Food Nutr. Sci.* **2020**, *11*, 481–508. [CrossRef]
7. Mehta, N.; Kumar, P.; Verma, A.K.; Umaraw, P.; Kumar, Y.; Malav, O.P.; Sazili, A.Q.; Domínguez, R.; Lorenzo, J.M. Microencapsulation as a Noble Technique for the Application of Bioactive Compounds in the Food Industry: A Comprehensive Review. *Appl. Sci.* **2022**, *12*, 1424. [CrossRef]
8. Arenas-Jal, M.; Suñé-Negre, J.M.; García-Montoya, E. An Overview of Microencapsulation in the Food Industry: Opportunities, Challenges, and Innovations. *Eur. Food Res. Technol.* **2020**, *246*, 1371–1382. [CrossRef]
9. Ćujić-Nikolić, N.; Stanisavljević, N.; Šavikin, K.; Kalušević, A.; Nedović, V.; Bigović, D.; Janković, T. Application of Gum Arabic in the Production of Spray-Dried Chokeberry Polyphenols, Microparticles Characterisation and in Vitro Digestion Method. *Lek. Sirovine* **2018**, *2020*, 9–16. [CrossRef]
10. Gheonea (Dima), I.; Aprodu, I.; Cîrciumaru, A.; Râpeanu, G.; Bahrim, G.E.; Stănciuc, N. Microencapsulation of Lycopene from Tomatoes Peels by Complex Coacervation and Freeze-Drying: Evidences on Phytochemical Profile, Stability and Food Applications. *J. Food Eng.* **2020**, *288*, 110166. [CrossRef]
11. Bhagya Raj, G.V.S.; Dash, K.K. Microencapsulation of Betacyanin from Dragon Fruit Peel by Complex Coacervation: Physicochemical Characteristics, Thermal Stability, and Release Profile of Microcapsules. *Food Biosci.* **2022**, *49*, 101882. [CrossRef]

12. Tylkowski, B.; Tsibranska, I. Polyphenols Encapsulation—Application of Innovation Technologies to Improve Stability of Natural Products. *Phys. Sci. Rev.* **2019**, *1*, 20150005. [CrossRef]
13. Lu, W.; Kelly, A.L.; Miao, S. Emulsion-Based Encapsulation and Delivery Systems for Polyphenols. *Trends Food Sci. Technol.* **2016**, *47*, 1–9. [CrossRef]
14. Nath, P.C.; Debnath, S.; Sridhar, K.; Inbaraj, B.S.; Nayak, P.K.; Sharma, M. A Comprehensive Review of Food Hydrogels: Principles, Formation Mechanisms, Microstructure, and Its Applications. *Gels* **2023**, *9*, 1. [CrossRef] [PubMed]
15. Hanula, M.; Szpicer, A.; Górska-Horczyczak, E.; Khachatryan, G.; Pogorzelska-Nowicka, E.; Poltorak, A. Quality of Beef Burgers Formulated with Fat Substitute in a Form of Freeze-Dried Hydrogel Enriched with Açai Oil. *Molecules* **2022**, *27*, 3700. [CrossRef] [PubMed]
16. Kakran, M.; Antipina, M.N. Emulsion-Based Techniques for Encapsulation in Biomedicine, Food and Personal Care. *Curr. Opin. Pharmacol.* **2014**, *18*, 47–55. [CrossRef] [PubMed]
17. Luo, S.; Chen, J.; Zeng, Y.; Dai, J.; Li, S.; Yan, J.; Liu, Y. Effect of Water-in-Oil-in-Water (W/O/W) Double Emulsions to Encapsulate Nisin on the Quality and Storage Stability of Fresh Noodles. *Food Chem. X* **2022**, *15*, 100378. [CrossRef] [PubMed]
18. Saqib, M.N.; Khaled, B.M.; Liu, F.; Zhong, F. Hydrogel Beads for Designing Future Foods: Structures, Mechanisms, Applications, and Challenges. *Food Hydrocoll. Health* **2022**, *2*, 100073. [CrossRef]
19. Di Girolamo, S.; Puorger, C.; Lipps, G. Stable and Selective Permeable Hydrogel Microcapsules for High-Throughput Cell Cultivation and Enzymatic Analysis. *Microb. Cell Fact.* **2020**, *19*, 170. [CrossRef] [PubMed]
20. Hanula, M.; Szpicer, A.; Górska-Horczyczak, E.; Khachatryan, G.; Pogorzelski, G.; Pogorzelska-Nowicka, E.; Poltorak, A. Hydrogel Emulsion with Encapsulated Safflower Oil Enriched with Açai Extract as a Novel Fat Substitute in Beef Burgers Subjected to Storage in Cold Conditions. *Molecules* **2022**, *27*, 2397. [CrossRef]
21. Nath, P.C.; Debnath, S.; Sharma, M.; Sridhar, K.; Nayak, P.K.; Inbaraj, B.S. Recent Advances in Cellulose-Based Hydrogels: Food Applications. *Foods* **2023**, *12*, 350. [CrossRef]
22. Li, M.; He, X.; Zhao, R.; Shi, Q.; Nian, Y.; Hu, B. Hydrogels as Promising Carriers for the Delivery of Food Bioactive Ingredients. *Front. Nutr.* **2022**, *9*, 1006520. [CrossRef] [PubMed]
23. Martins, E.; Poncelet, D.; Rodrigues, R.C.; Renard, D. Oil Encapsulation Techniques Using Alginate as Encapsulating Agent: Applications and Drawbacks. *J. Microencapsul.* **2017**, *34*, 754–771. [CrossRef]
24. da Silva, L.C.; Castelo, R.M.; Cheng, H.N.; Biswas, A.; Furtado, R.F.; Alves, C.R. Methods of Microencapsulation of Vegetable Oil: Principles, Stability and Applications—A Minireview. *Food Technol. Biotechnol.* **2022**, *60*, 308–320. [CrossRef]
25. Rigon, R.T.; Zapata Noreña, C.P. Microencapsulation by Spray-Drying of Bioactive Compounds Extracted from Blackberry (*Rubus Fruticosus*). *J. Food Sci. Technol.* **2016**, *53*, 1515–1524. [CrossRef] [PubMed]
26. Szpicer, A.; Onopiuk, A.; Barczak, M.; Kurek, M. The Optimization of a Gluten-Free and Soy-Free Plant-Based Meat Analogue Recipe Enriched with Anthocyanins Microcapsules. *LWT* **2022**, *168*, 113849. [CrossRef]
27. Piñón-Balderrama, C.I.; Leyva-Porras, C.; Terán-Figueroa, Y.; Espinosa-Solís, V.; Álvarez-Salas, C.; Saavedra-Leos, M.Z. Encapsulation of Active Ingredients in Food Industry by Spray-Drying and Nano Spray-Drying Technologies. *Processes* **2020**, *8*, 889. [CrossRef]
28. Assadpour, E.; Jafari, S.M. Advances in Spray-Drying Encapsulation of Food Bioactive Ingredients: From Microcapsules to Nanocapsules. *Annu. Rev. Food Sci. Technol.* **2019**, *10*, 103–131. [CrossRef]
29. Furuta, T.; Neoh, T.L. Microencapsulation of Food Bioactive Components by Spray Drying: A Review. *Dry. Technol.* **2021**, *39*, 1800–1831. [CrossRef]
30. Gharsallaoui, A.; Roudaut, G.; Chambin, O.; Voilley, A.; Saurel, R. Applications of Spray-Drying in Microencapsulation of Food Ingredients: An Overview. *Food Res. Int.* **2007**, *40*, 1107–1121. [CrossRef]
31. Kandasamy, S.; Naveen, R. A Review on the Encapsulation of Bioactive Components Using Spray-Drying and Freeze-Drying Techniques. *J. Food Process Eng.* **2022**, *45*, e14059. [CrossRef]
32. Ogrodowska, D.; Tanska, M.; Brandt, W.; Czaplicki, S. Impact of the Encapsulation Process by Spray- And Freeze-Drying on the Properties and Composition of Powders Obtained from Cold-Pressed Seed Oils with Various Unsaturated Fatty Acids. *Pol. J. Food Nutr. Sci.* **2020**, *70*, 241–252. [CrossRef]
33. Rezvankhah, A.; Emam-Djomeh, Z.; Askari, G. Encapsulation and Delivery of Bioactive Compounds Using Spray and Freeze-Drying Techniques: A Review. *Dry. Technol.* **2020**, *38*, 235–258. [CrossRef]
34. Fang, Z.; Bhandari, B. *Spray Drying, Freeze Drying and Related Processes for Food Ingredient and Nutraceutical Encapsulation*; Elsevier: Amsterdam, The Netherlands, 2012. [CrossRef]
35. Zhao, Y.; Khalid, N.; Shu, G.; Neves, M.A.; Kobayashi, I.; Nakajima, M. Complex Coacervates from Gelatin and Octenyl Succinic Anhydride Modified Kudzu Starch: Insights of Formulation and Characterization. *Food Hydrocoll.* **2019**, *86*, 70–77. [CrossRef]
36. Tatasciore, S.; Santarelli, V.; Neri, L.; González Ortega, R.; Faieta, M.; Di Mattia, C.D.; Di Michele, A.; Pittia, P. Freeze-Drying Microencapsulation of Hop Extract: Effect of Carrier Composition on Physical, Techno-Functional, and Stability Properties. *Antioxidants* **2023**, *12*, 442. [CrossRef]
37. Abdul Mudalip, S.K.; Khatiman, M.N.; Hashim, N.A.; Che Man, R.; Arshad, Z.I.M. A Short Review on Encapsulation of Bioactive Compounds Using Different Drying Techniques. *Mater. Today Proc.* **2019**, *42*, 288–296. [CrossRef]
38. Kamali Rousta, L.; Bodbodak, S.; Nejatian, M.; Ghandehari Yazdi, A.P.; Rafiee, Z.; Xiao, J.; Jafari, S.M. Use of Encapsulation Technology to Enrich and Fortify Bakery, Pasta, and Cereal-Based Products. *Trends Food Sci. Technol.* **2021**, *118*, 688–710. [CrossRef]

39. Trilokia, M.; Campus Chatha, M.; Julie Bandral, I.D.; Ankita Chib, I.; Preeti Choudhary Agromet Observer, I.; Corresponding Author, I.; Bandral, J.D.; Chib, A.; Choudhary, P. Microencapsulation for Food: An Overview. *Pharma. Innov. J.* **2022**, *11*, 1174–1180.
40. Mohammadalinejhad, S.; Kurek, M.A. Microencapsulation of Anthocyanins—Critical Review of Techniques and Wall Materials. *Appl. Sci.* **2021**, *11*, 3936. [CrossRef]
41. Soumya, S.B.S.; Sawant, A.A.; Khandetod, Y.P. Microencapsulation Techniques Used for Underutilized Fruits of Western Ghat: An Overview. *Pharma Innov. J.* **2021**, *10*, 826–833.
42. Chen, H.W.; Chang, Y.W.; Fang, W.P. A New Approach for the Microencapsulation of Clitoria Ternatea Petal Extracts by a High-Pressure Processing Method. *Pharmaceutics* **2021**, *13*, 23. [CrossRef]
43. Subramani, T.; Ganapathyswamy, H. An Overview of Liposomal Nano-Encapsulation Techniques and Its Applications in Food and Nutraceutical. *J. Food Sci. Technol.* **2020**, *57*, 3545–3555. [CrossRef]
44. Ozkan, G.; Franco, P.; De Marco, I.; Xiao, J.; Capanoglu, E. A Review of Microencapsulation Methods for Food Antioxidants: Principles, Advantages, Drawbacks and Applications. *Food Chem.* **2019**, *272*, 494–506. [CrossRef] [PubMed]
45. Bhosale, S.; Desale, R.J.; Fulpagare, Y.G. Microencapsulation: Applications in the Different Dairy Products. *Int. J. Pharm. Biomed. Eng.* **2019**, *6*, 7–11. [CrossRef]
46. Fang, Z.; Bhandari, B. Encapsulation of Polyphenols—A Review. *Trends Food Sci. Technol.* **2010**, *21*, 510–523. [CrossRef]
47. Santos, P.D.F.; Rubio, F.T.V.; da Silva, M.P.; Pinho, L.S.; Favaro-Trindade, C.S. Microencapsulation of Carotenoid-Rich Materials: A Review. *Food Res. Int.* **2021**, *147*, 110571. [CrossRef] [PubMed]
48. Mirzamani, S.S.; Bassiri, A.; Tavakolipour, H.; Azizi, M.H.; Kargozari, M. Fluidized Bed Microencapsulation of Lactobacillus Sporogenes with Some Selected Hydrocolloids for Probiotic Bread Production. *J. Food Biosci. Technol.* **2021**, *11*, 23–34.
49. Pattnaik, M.; Pandey, P.; Martin, G.J.O.; Mishra, H.N.; Ashokkumar, M. Innovative Technologies for Extraction and Microencapsulation of Bioactives from Plant-Based Food Waste and Their Applications in Functional Food Development. *Foods* **2021**, *10*, 279. [CrossRef] [PubMed]
50. Jayaprakash, P.; Gaiani, C.; Edorh, J.-M.; Borges, F.; Beaupeux, E.; Maudhuit, A.; Desobry, S. Comparison of Electrostatic Spray Drying, Spray Drying, and Freeze Drying for Lacticaseibacillus Rhamnosus GG Dehydration. *Foods* **2023**, *12*, 3117. [CrossRef]
51. Jayaprakash, P.; Maudhuit, A.; Gaiani, C.; Desobry, S. Encapsulation of Bioactive Compounds Using Competitive Emerging Techniques: Electrospraying, Nano Spray Drying, and Electrostatic Spray Drying. *J. Food Eng.* **2023**, *339*, 111260. [CrossRef]
52. Macías-Cortés, E.; Gallegos-Infante, J.A.; Rocha-Guzmán, N.E.; Moreno-Jiménez, M.R.; Medina-Torres, L.; González-Laredo, R.F. Microencapsulation of Phenolic Compounds: Technologies and Novel Polymers. *Rev. Mex. Ing. Quim.* **2020**, *19*, 491–521. [CrossRef]
53. Reis, D.R.; Ambrosi, A.; Luccio, M. Di Encapsulated Essential Oils: A Perspective in Food Preservation. *Futur. Foods* **2022**, *5*, 100126. [CrossRef]
54. Bodbodak, S.; Nejatian, M.; Ghandehari Yazdi, A.P.; Kamali Rousta, L.; Rafiee, Z.; Jalali-Jivan, M.; Kharazmi, M.S.; Jafari, S.M. Improving the Thermal Stability of Natural Bioactive Ingredients via Encapsulation Technology. *Crit. Rev. Food Sci. Nutr.* **2022**, *9*, 1–23. [CrossRef] [PubMed]
55. Shaaban, H.A.; Farouk, A. Encapsulation of Essential Oils and Their Use in Food Applications. In *Essential Oils—Advances in Extractions and Biological Applications*; IntechOpen: London, UK, 2022; pp. 1–15.
56. Martins, E.; Poncelet, D.; Renard, D. A Novel Method of Oil Encapsulation in Core-Shell Alginate Microcapsules by Dispersion-Inverse Gelation Technique. *React. Funct. Polym.* **2017**, *114*, 49–57. [CrossRef]
57. González, A.; Bordón, M.G.; Bustos, M.C.; Córdova Salazar, K.L.; Ribotta, P.D.; Martínez, M.L. Study of the Incorporation of Native and Microencapsulated Chia Seed Oil on Pasta Properties. *Int. J. Food Sci. Technol.* **2021**, *56*, 233–241. [CrossRef]
58. Iafelice, G.; Caboni, M.F.; Cubadda, R.; Di Criscio, T.; Trivisonno, M.C.; Marconi, E. Development of Functional Spaghetti Enriched with Long Chain Omega-3 Fatty Acids. *Cereal Chem.* **2008**, *85*, 146–151. [CrossRef]
59. Verardo, V.; Ferioli, F.; Riciputi, Y.; Iafelice, G.; Marconi, E.; Caboni, M.F. Evaluation of Lipid Oxidation in Spaghetti Pasta Enriched with Long Chain $N-3$ Polyunsaturated Fatty Acids under Different Storage Conditions. *Food Chem.* **2009**, *114*, 472–477. [CrossRef]
60. Pashaei, N.; Salehifar, M.; Fahimdanesh, M. Evaluation of Stability Omega-3 Fatty Acids Stability in Different Drying Conditions and Its Microencapsulated Retention in Enriched Spaghetti. *J. Food Technol. Nutr.* **2020**, *17*, 39–48.
61. Jeyakumari, A.; Zynudheen, A.; Murthy, L.; Parvathy, U. Effect of Sodium Alginate/Carrageenan Composites on the Oxidative Stability of Microencapsulated Fish Oil and Its Application in Noodles. *ICAR-Cent. Inst. Fish. Technol.* **2017**, *Asian Fish*, 368.
62. Durante, M.; Lenucci, M.S.; Gazza, L.; Taddei, F.; Nocente, F.; De Benedetto, G.E.; De Caroli, M.; Piro, G.; Mita, G. Bioactive Composition and Sensory Evaluation of Innovative Spaghetti Supplemented with Free or α-Cyclodextrin Chlatrated Pumpkin Oil Extracted by Supercritical CO_2. *Food Chem.* **2019**, *294*, 112–122. [CrossRef]
63. Trigo, J.P.; Alexandre, E.M.C.; Saraiva, J.A.; Pintado, M.E. High Value-Added Compounds from Fruit and Vegetable by-Products–Characterization, Bioactivities, and Application in the Development of Novel Food Products. *Crit. Rev. Food Sci. Nutr.* **2020**, *60*, 1388–1416. [CrossRef]
64. Leri, M.; Scuto, M.; Ontario, M.L.; Calabrese, V.; Calabrese, E.J.; Bucciantini, M.; Stefani, M. Healthy Effects of Plant Polyphenols: Molecular Mechanisms. *Int. J. Mol. Sci.* **2020**, *21*, 1250. [CrossRef]
65. Fraga, C.G.; Croft, K.D.; Kennedy, D.O.; Tomás-Barberán, F.A. The Effects of Polyphenols and Other Bioactives on Human Health. *Food Funct.* **2019**, *10*, 514–528. [CrossRef] [PubMed]

66. Chaouch, M.A.; Benvenuti, S. The Role of Fruit By-Products as Bioactive Compounds for Intestinal Health. *Foods* **2020**, *9*, 1716. [CrossRef] [PubMed]
67. Batista, V.S.F.; Nunes, G.L.; da Silva, A.F.M.; Viegas, G.I.; Lucas, B.N.; Barin, J.S.; de Menezes, C.R.; da Rosa, C.S. Addition of Microencapsulated Soybean Molasses to Pasta Formulations. *Cienc. Rural* **2021**, *51*, e20200722. [CrossRef]
68. Mehran, M.; Masoum, S.; Memarzadeh, M. Improvement of Thermal Stability and Antioxidant Activity of Anthocyanins of Echium Amoenum Petal Using Maltodextrin/Modified Starch Combination as Wall Material. *Int. J. Biol. Macromol.* **2020**, *148*, 768–776. [CrossRef] [PubMed]
69. Zhang, Z.H.; Wang, Y.; Ho, C.T.; Patiguli, M.; Zhang, Y.; Yu, B.; Zhang, C.; Aadil, R.M.; Qu, W.; Xiao, R.; et al. Addition of Chlorophyll Microcapsules to Improve the Quality of Fresh Wheat Noodles. *Learn. Technol.* **2023**, *183*, 114940. [CrossRef]
70. Ćetković, G.; Šeregelj, V.; Brandolini, A.; Čanadanović-Brunet, J.; Tumbas Šaponjac, V.; Vulić, J.; Šovljanski, O.; Četojević-Simin, D.; Škrobot, D.; Mandić, A.; et al. Composition, Texture, Sensorial Quality, and Biological Activity after in Vitro Digestion of Durum Wheat Pasta Enriched with Carrot Waste Extract Encapsulates. *Int. J. Food Sci. Nutr.* **2022**, *73*, 638–649. [CrossRef] [PubMed]
71. Zen, C.K.; Tiepo, C.B.V.; da Silva, R.V.; Reinehr, C.O.; Gutkoski, L.C.; Oro, T.; Colla, L.M. Development of Functional Pasta with Microencapsulated Spirulina: Technological and Sensorial Effects. *J. Sci. Food Agric.* **2020**, *100*, 2018–2026. [CrossRef] [PubMed]
72. Elsebaie, E.M.; Asker, G.A.; Mousa, M.M.; Kassem, M.M.; Essa, R.Y. Technological and Sensory Aspects of Macaroni with Free or Encapsulated Azolla Fern Powder. *Foods* **2022**, *11*, 707. [CrossRef]
73. Šeregelj, V.; Škrobot, D.; Kojić, J.; Pezo, L.; Šovljanski, O.; Šaponjac, V.T.; Vulić, J.; Hidalgo, A.; Brandolini, A.; Čanadanović-Brunet, J.; et al. Quality and Sensory Profile of Durum Wheat Pasta Enriched with Carrot Waste Encapsulates. *Foods* **2022**, *11*, 1130. [CrossRef]
74. Singh, P.; Bohra, A.; Sheoran, S.; Arora, S. Microencapsulation of Ferulic Acid from Vegetables Waste and Its Application in Pasta. *Int. J. Res. Anal. Rev.* **2019**, *6*, 674–686.
75. Safeer Abbas, M.; Afzaal, M.; Saeed, F.; Asghar, A.; Jianfeng, L.; Ahmad, A.; Ullah, Q.; Elahi, S.; Ateeq, H.; Shah, Y.A.; et al. Probiotic Viability as Affected by Encapsulation Materials: Recent Updates and Perspectives. *Int. J. Food Prop.* **2023**, *26*, 1324–1350. [CrossRef]
76. Sbehat, M.; Mauriello, G.; Altamimi, M. Microencapsulation of Probiotics for Food Functionalization: An Update on Literature Reviews. *Microorganisms* **2022**, *10*, 1948. [CrossRef]
77. Tolve, R.; Galgano, F.; Caruso, M.C.; Tchuenbou-Magaia, F.L.; Condelli, N.; Favati, F.; Zhang, Z. Encapsulation of Health-Promoting Ingredients: Applications in Foodstuffs. *Int. J. Food Sci. Nutr.* **2016**, *67*, 888–918. [CrossRef] [PubMed]
78. De Prisco, A.; Mauriello, G. Probiotication of Foods: A Focus on Microencapsulation Tool. *Trends Food Sci. Technol.* **2016**, *48*, 27–39. [CrossRef]
79. Rajam, R.; Subramanian, P. Encapsulation of Probiotics: Past, Present and Future. *Beni-Suef Univ. J. Basic Appl. Sci.* **2022**, *11*, 46. [CrossRef]
80. Alkan, S. Production of Functional Turkish Noodle (Erişte) Supplementary Probiotic and Determining of Some Quality Properties. *Food Health* **2020**, *6*, 140–150. [CrossRef]
81. Rajam, R.; Kumar, S.B.; Prabhasankar, P.; Anandharamakrishnan, C. Microencapsulation of Lactobacillus Plantarum MTCC 5422 in Fructooligosaccharide and Whey Protein Wall Systems and Its Impact on Noodle Quality. *J. Food Sci. Technol.* **2015**, *52*, 4029–4041. [CrossRef] [PubMed]
82. Dhakal, S.P.; He, J. Microencapsulation of Vitamins in Food Applications to Prevent Losses in Processing and Storage: A Review. *Food Res. Int.* **2020**, *137*, 109326. [CrossRef] [PubMed]
83. Baldelli, A.; Ren, M.; Liang, D.Y.; Lai, S.; Hartono, B.; Sum, K.; Pratap-Singh, A. Sprayed Microcapsules of Minerals for Fortified Food. *J. Funct. Foods* **2023**, *101*, 105401. [CrossRef]
84. Maurya, V.K.; Bashir, K.; Aggarwal, M. Vitamin D Microencapsulation and Fortification: Trends and Technologies. *J. Steroid Biochem. Mol. Biol.* **2020**, *196*, 105489. [CrossRef] [PubMed]
85. Estevinho, B.N.; Lazar, R.; Blaga, A.; Rocha, F. Preliminary Evaluation and Studies on the Preparation, Characterization and in Vitro Release Studies of Different Biopolymer Microparticles for Controlled Release of Folic Acid. *Powder Technol.* **2020**, *369*, 279–288. [CrossRef]
86. Liu, Y.; Green, T.J.; Kitts, D.D. Stability of Microencapsulated L-5-Methyltetrahydrofolate in Fortified Noodles. *Food Chem.* **2015**, *171*, 206–211. [CrossRef] [PubMed]
87. Yingleardrattanakul, P.; Thompson, A.K.; Taprap, R.; Pinsirodom, P.; Bindu, C. Evaluation of the Efficiency of Various Folic Acid Microencapsulation Techniques for Rice Vermicelli (Khanom Jeen) Fortification. *Food Humanit.* **2024**, *2*, 100198. [CrossRef]