Food Chemistry Research on Optimizing Nutrient Embedding and Release in Baked Goods Using Microcapsule Technology

Junming Feng

Zhuhai Oriental Yinghua International Academy, Zhuhai, China

junmingfengapp@163.com

Keywords: Microcapsule technology; Nutritional optimization; Baked goods; Structural stability; Intelligent release system

Abstract: Microcapsule technology can help baked goods hold and release nutrients better. This solves the problem of low efficiency that happens when standard nutritional reinforcement is done in a way that causes excessive heat and oxidation. This article examines the structural stability, release model, and control strategy of microcapsule technology in the baking process from a food chemistry standpoint, while also investigating the simultaneous improvement of wall material design and modification, preparation process optimization, and intelligent release systems. Research has demonstrated that the selection of appropriate wall materials and methods, informed by nutritional properties, is essential for enhancing nutrient retention and release coordination. This technology will use new materials and smart control systems to help make baked goods that work, which will lead to smart and efficient use of nutrition.

1. Introduction

1.1. Research Background

People around the world love baked products because they are easy to make and taste wonderful. But conventional baked goods often have drawbacks like having only one type of nutrients and not enough useful ingredients. As people become more aware of their health, the main goal of the baking industry is to make baked goods healthier by adding nutrients. Adding functional ingredients like vitamins (like vitamin C and B vitamins), probiotics, omega-3 polyunsaturated fatty acids, and plant polyphenols is one of the most important ways to do this. But most of these nutrients are sensitive to heat, oxidation, or acidic and alkaline conditions. During the baking process, when the temperature is high (150-220℃), the humidity is high, and the substrates are complicated (like gluten networks in flour and oil oxidation products), they are likely to break down, deactivate, or move, which means that the actual retention rate is less than 30%. This makes nutritional enhancement much less effective [1].

The old direct addition method doesn't work anymore since it can't handle the damage that baking does. Microcapsule technology wraps nutrients (core material) around polymer materials (wall material) to make micro capsules. These capsules can protect the core material from damage from the outside world, like high temperatures, oxygen, and enzymatic hydrolysis. They can also control the release process, which is a new way to solve the main problem with improving the nutritional value of baked goods. Microcapsule technology has shown promise in dairy products, drinks, and other fields thus far. But the special way baked goods are made (high temperature, long-term heating, and moving moisture) makes it harder for microcapsule stability, core material retention rate, and release coordination to work. Current research lacks comprehensive understanding of the compatibility of microcapsule wall materials with baking processes, as well as the food chemistry principles regulating nutrient release mechanisms, hence constraining their precise application in boosting nutrition in baked products. Consequently, a comprehensive examination of the nutritional embedding and release mechanisms of microcapsule technology in baking environments holds substantial theoretical and practical significance.

  DOI: 10.25236/iwmecs.2025.052

1.2. Research Objective

The goal of this research is to systematically investigate the key mechanisms and regulation techniques of microcapsule technology in improving the embedding and release of nutrients in baked products from the standpoint of food chemistry. Specific aims include, as demonstrated in Figure 1.

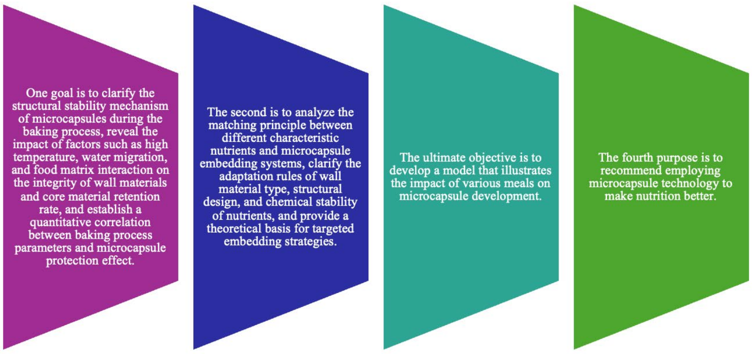

Figure 1: The four goals of this research.

One goal is to clarify the structural stability mechanism of microcapsules during the baking process, reveal the impact of factors such as high temperature, water migration, and food matrix interaction on the integrity of wall materials and core material retention rate, and establish a quantitative correlation between baking process parameters and microcapsule protection effect [2].

The second is to analyze the matching principle between different characteristic nutrients (such as hydrophilic vitamins, hydrophobic unsaturated fatty acids, thermosensitive probiotics) and microcapsule embedding systems, clarify the adaptation rules of wall material type, structural design, and chemical stability of nutrients, and provide a theoretical basis for targeted embedding strategies.

The ultimate objective is to develop a model that illustrates the impact of various meals on microcapsule development. This model will look at how wall deterioration, core diffusion, and food matrix interaction affect the release rate during storage and digesting after baking [3].

The fourth purpose is to recommend employing microcapsule technology to make nutrition better. To fix the problems of poor stability and uncoordinated release in present nutrition improvement, we need to make changes to the wall, improve the preparation process, and work together to make the baking conditions better. This presents a scientific basis for manufacturing baked goods that work.

2. Basic Principles and Preparation Methods of Microcapsule Technology

There are the basic principles and preparation methods of microcapsule technology, such as Structure and Functional Characteristics of Microcapsules, Preparation Method and Optimization of Microcapsules, and Selection and Modification Strategy of Wall Materials, as shown in Figure 2.

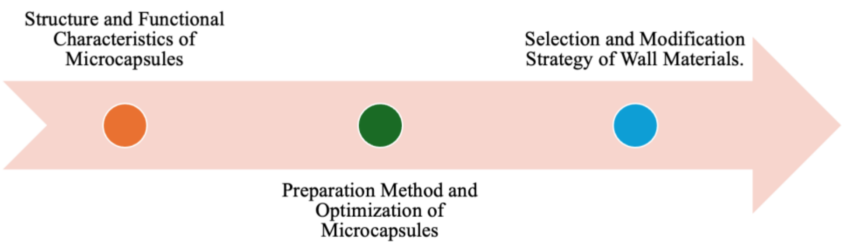

Figure 2: Basic principles and preparation methods of microcapsule technology.

2.1. Structure and Functional Characteristics of Microcapsules

Microcapsules are microencapsulation structures formed by specific processes between core and wall materials. They are distinguished by the synergistic effect of isolation, protection, and controlled release. In terms of structural composition, the core material is the nutritious components that need to be preserved (such as vitamins, probiotics, and so on), while the wall material is the polymer material with barrier function. Through interface contact, the two produce a core-shell structure, multi-core structure, or composite network structure. In the core-shell structure, the wall material forms a continuous thin film to wrap around the core material, which is appropriate for single component embedding. Wall materials separate the multi-core structure into several core material locations. This makes it possible to embed various components together [4]. The composite network structure creates a three-dimensional porous network by joining wall materials together in different ways. This makes the support environment for the core material stronger.

In terms of functional properties, its core function is based on the interface effect of food chemistry: first, the physical isolation function, in which the wall material forms a dense structure through intermolecular forces (such as hydrogen bonding, van der Waals forces), which can isolate the damage of external factors such as oxygen, moisture, and high temperature to the core material, such as the oxidation-sensitive omega-3 fatty acids. The wall material can keep them from coming into contact with oxygen and slow down the oxidation process. The second function is controlled release, where the wall material's dissolution, degradation, or swelling is controlled by things like temperature and pH. This lets the core material be released at a set rate during certain stages (like storage and digestion after baking), which keeps nutrients from being lost too soon when the temperature is high. The wall material can hide the core material's bad taste (like the fishy smell of fish oil), make it easier for the food matrix to spread out (like the even distribution of fat-soluble components in the aqueous matrix), and lessen the core material's bad effect on food texture (like the extensibility of dough). The size (1–1000μm) and surface properties (hydrophilicity and hydrophobicity) of the particles in microcapsules affect how well they mix with baked dough. These are crucial structural factors for how well they work and how they release their contents.

2.2. Preparation Method and Optimization of Microcapsules

Microcapsule preparation techniques are classified into three groups depending on the interface contact mechanism between the core and wall materials: physical, chemical, and physicochemical. The primary difference is in the driving force and structural management of wall material production.

The physical approach of coating is based on mechanical force or phase separation. Spray drying and freeze drying are typical approaches. The spray drying process allows the solvent to evaporate quickly, forming microcapsules by atomizing the core wall lotion and contacting the hot air flow. Its primary factors are air inlet temperature (which affects the curing rate of the wall material) and lotion solids concentration (which affects particle size and compactness). Adjust the atomization pressure (0.2-0.5 MPa) and hot air rate to maximize drying efficiency and minimize core material deterioration caused by high temperatures. The freeze-drying process, which eliminates the solvent by vacuum sublimation after freezing the lotion at a low temperature, is suited for heat sensitive materials. The optimization focuses on pre-freezing temperature (-40 to -20℃) and vacuum degree (10-30Pa) to avoid ice crystals from damaging the wall structure [5].

Wall materials are generated by chemical processes such as interfacial polymerization. At the oil-water lotion interface, wall monomers (such as isocyanate and amine) polymerize to produce a polymer film. Its primary optimization factors are the monomer concentration ratio (which impacts crosslinking degree) and reaction time (which regulates wall material thickness). Controlling the reaction temperature (25-60 ℃) helps prevent heat-induced core material inactivation.

The physical chemistry method is based on phase separation and interface adsorption, as represented by the complex condensation method: two wall materials with opposing charges (such as gelatin and arabic gum) are used to neutralize charges at a specific pH, resulting in a condensed phase coating core material. The pH value (which affects charge density) and the amount of wall material (which determines condensed phase viscosity) are the most important criteria for optimization. Adding 0.1–0.5% NaCl to the ion strength may make the condensed phase more uniform.

The aim of optimization methods are to get high embedding rates (over 80%), stability (over 90%), and the ability to modify the size of the particles (1–50 μm). You should consider about the qualities of the core material while picking the suitable techniques.

2.3. Selection and Modification Strategy of Wall Materials

There are three things that wall materials must meet: they must be safe, they must be able to adapt to different processes, and they must be able to act as a barrier. The major purpose is to suit the needs of baked goods that need to be processed at high temperatures and keep their nutrients. There are three main types: natural polymer materials, synthetic polymer materials, and composite wall materials.

Natural polymer materials, such proteins (gelatin, whey protein) and polysaccharides (chitosan, starch), are the most preferred choice right now since they are biocompatible and break down on their own. Intramolecular hydrophobic interactions make protein wall materials create dense structures, but they don't hold up well to heat (the glass transition temperature is around 60–80 °C), thus they need to be changed to be able to handle high temperatures. For example, the Maillard reaction and the breaking of sugar cross-linking may elevate the temperature at which the material breaks down to more than 120°C. Polysaccharide wall materials, such hydroxypropyl methyl cellulose, are great for making films, however they aren't robust enough. Adding 1–5% nanocellulose to a material may make it stronger by generating a network of different materials [6] .

Polylactic acid (PLA) and polybutylene adipate (PBAT) are examples of synthetic polymer materials that are exceptionally strong and stable at high temperatures (decomposition temperature>200°C). However, they don't function well with living creatures. The modification process includes adding hydrophilic groups, such polyethylene glycol segments, to reduce interfacial tension, making it simpler to mix with food, and lessen the possibility of causing gastrointestinal pain.

Using the combined effects of many materials, composite wall materials fix the problems with single materials. For example, protein, polysaccharide, and inorganic nanoparticle composite systems work together to make the wall stronger. Proteins make the wall more stable by making the surface more active, polysaccharides make the wall more stable by filling in gaps, and nanoparticles (like silica, which is 5–20nm in size) make the wall denser. The ratio of the parts (for example, protein to polysaccharide = 1:1 to 3:1) is the most significant portion of optimization. When baked at 180 °C, it may lessen the pace at which wall materials break down by more than 30%.

The major goal of modification is to make the wall material more resistant to high temperatures (glass transition temperature>150°C), water (water contact angle >90°), and degradation that may be regulated. Chemical crosslinking (like glutaraldehyde crosslinking), physical modification (like heat treatment that makes crystals), or enzymatic modification (like transglutaminase-catalyzed crosslinking) can change the wall material to make it work better in the high heat and humidity of baking. This protects the core material at all times.

3. Factors Affecting Nutrient Embedding and Release during Baking Process

There are factors affecting nutrient embedding and release during baking process, such as Mechanism of Baking Process Parameters, Compatibility between Nutritional Characteristics and Embedding Strategies, and Interactions between Food Matrices, as demonstrated in Figure 3.

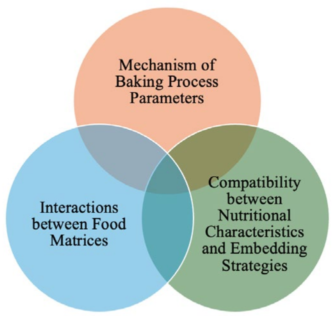

Figure 3: Factors affecting nutrient embedding and release during baking process.

3.1. Mechanism of Baking Process Parameters

The parameters of the baking process have a direct effect on the stability of the wall structure and the way the core material is released by affecting the physical and chemical environment of the microcapsules. The fundamental process is predicated on the synergistic interaction between thermodynamics and phase transition. The temperature is the most important factor. When the baking temperature goes above the wall material's glass transition temperature (Tg), the molecules in the wall material move more, changing from a glassy state to a rubbery state. This makes the structure less dense and causes the core material to leak too soon. If the temperature goes up even further (like above 200°C), natural polymer wall materials (like gelatin) may break down from heat, which breaks the main chain and makes a porous structure. This makes the core material lose its ability to hold onto things quickly [7]. Time makes temperature have a bigger impact by adding up thermal effects, and a longer baking time may make wall oxidation worse (as when oily wall materials get rancid), which can damage the coating's integrity.

Humidity and moisture migration are equally important: high humidity in the early stages of baking (dough moisture content of 30%~40%) can cause hydrophilic wall materials (such as starch) to swell, increase molecular gaps, and make the core material easily lose through moisture diffusion; Low humidity environment in the later stage (with moisture content reduced to 5%~10%) may lead to excessive shrinkage of the wall material, resulting in cracks. The pH value of dough, which is normally between 5.0 and 6.5, also controls how much it swells by changing the charge state of the wall material. For example, in acidic circumstances, cationic wall materials like chitosan improve hydrogen bonding via protonation, which makes the structure more stable. When the pH is high, anionic wall materials like sodium alginate may lose protons, which makes the structure loose. The synergistic impact of these factors affects the core material retention rate of microcapsules during baking, which is the most important element in how well nutrients are encapsulated.

3.2. Compatibility between Nutritional Characteristics and Embedding Strategies

The protective effect and release coordination of microcapsules depend directly on the inherent properties of the nutritional components (hydrophilicity, hydrophobicity, thermal stability, and chemical activity) and how well they fit with their embedding strategies. This is basically the adaptability of the core wall interface forces. Hydrophilic substances, including vitamin C and water-soluble dietary fiber, have a lot of hydroxyl and carboxyl groups that may readily interact with water molecules. To build a barrier between water and oil, you need to use wall materials that don't like water, including plant oils and modified starch. Loss may be lessened by lowering the chance that the core material will come into contact with water from the environment. If you employ hydrophilic wall materials incorrectly, the embedding rate may be less than 50% because they may dissolve in each other.

Due to the high intermolecular van der Waals force, hydrophobic parts like ω -3 fatty acids and fat-soluble vitamins tend to group together. To make an oil-water lotion system, you need to employ hydrophilic wall components like gelatin and gum arabic. These materials may be equally spread out by mixing them together. At the same time, it needs to make the wall materials denser by cross-linking them to stop baking oil from dissolving the core components. Thermally sensitive ingredients (like probiotics and enzyme preparations) lose their effectiveness above 60°C. To keep them safe, they should be embedded in a way that combines low-temperature preparation methods (like freeze-drying) with high-temperature resistant wall materials (like modified chitosan). This will slow down heat conduction through the insulation effect of the wall materials (reducing thermal conductivity by 20% to 30%) and match short-term high-temperature baking processes to reduce heat exposure. Also, oxidation-sensitive parts like polyphenols and unsaturated fatty acids need to add antioxidant groups (like phenolic hydroxyl groups) to the wall material to slow down the degradation of the core material by working together with the antioxidant groups. The main part of its embedding approach is the combination of physical separation and chemical protection.

3.3. Interactions between Food Matrices

Under the interaction of intermolecular forces and microcapsules, baking food matrices (such as flour, oil, emulsifiers, salts) undergo very complex interactions, which can have profound and significant changes in embedding stability and release kinetics. Essentially, it is a regulatory behavior between interfacial tension and thermodynamic equilibrium in multiphase systems. The gluten proteins (gliadin and gliadin) in flour can adsorb on the surface of microcapsules through hydrophobic interactions and hydrogen bonding. If the wall material is hydrophilic (e.g., starch), increased adsorption may cause microcapsule aggregation and reduce the dispersion uniformity of the core material; hydrophobic wall materials (e.g., beeswax) can reduce affinity with gluten proteins, improve dispersibility, but may reduce dough extensibility [8].

The gelatinization of starch (60-80 ℃) has a dual effect on the structure of microcapsules. The stretched starch molecular chains may fill the gaps between microcapsules to enhance mechanical protection, but the high viscosity of excessive starch paste can hinder the release of the core material in the later stage. Oil, as a hydrophobic matrix, has a competitive dissolution effect on fat-soluble core materials; when the baking oil content exceeds 20%, its similar solubility with core materials such as omega-3 fatty acids accelerates core material migration from the wall material, resulting in a 15% to 25% decrease in embedding rate.

Emulsifiers (such as monoglycerides) influence microcapsule stability by lowering interfacial tension: at low concentrations, they can improve compatibility between the wall material and the matrix, whereas at high concentrations, they can penetrate the wall material to form channels, promoting early release of the core material. Furthermore, the ionic strength of salts (such as NaCl) may influence the charge density of the wall material. For example, in a high salt environment, chitosan protonation is hindered, resulting in decreased wall swelling and delaying the release of the core material. The interaction of these matrices with microcapsules demonstrates concentration dependency and synergy, which is an important environmental element controlling nutrient embedding and release in baked products.

4. Optimization of Nutrient Embedding and Release Strategies Using Microcapsule Technology

There are optimization of nutrient embedding and release strategies using microcapsule technology, including Precise Control of Wall Material Design and Modification, Collaborative Optimization of Preparation Process, and Release Dynamics Model and Intelligent System Design, as shown in Figure 4.

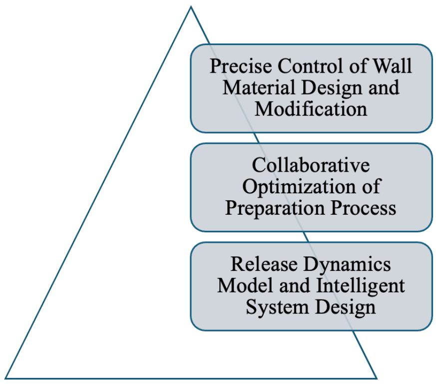

Figure 4: Optimization of nutrient embedding and release strategies using microcapsule technology.

4.1. Precise Control of Wall Material Design and Modification

Wall materials are important in microcapsule technology because they affect how well nutrients are released and how well they are encapsulated. Molecular structure design can make wall materials more stable, more compatible, and more biodegradable. This protects nutrients better and allows for more precise release. If you use functionalized polymers or nanomaterials to make walls, they could become more sensitive and better at keeping things out. This would help them release nutrients at the correct time when baking. Also, the physical and chemical properties of wall materials, such as how well they hold up to water, how strong they are, and how stable they are at high temperatures, need to be carefully altered to meet the needs of various baking processes and healthy ingredients. This will let nutrients be delivered in a sensible way and remain in their capsules.

4.2. Collaborative Optimization of Preparation Process

If you want to get the most out of microcapsule technology in baked goods, you need to make sure that the manner they are manufactured is as good as it can be. To make sure that embedding works every time, think about the temperature, pressure, and how rapidly you stir. Second, better microencapsulation methods like spray drying, freeze drying, or emulsification might make it simpler to control the release of microcapsules. Microcapsules are more stable and flexible when they are created utilizing diverse methods, such as chemical crosslinking and physical embedding. Also, having full control over how different substances interact with each other during the preparation process could speed up the loading and release of nutrients by a large amount. This would make it easier to use microcapsule technology for baking.

4.3. Release Dynamics Model and Intelligent System Design

In the application of microcapsule technology, there is no doubt that the release kinetics model plays an important role, which directly affects the release time and release mode of nutrients during the baking process. Based on mathematical models and experimental data, an accurate release kinetics model can be established to predict the release of nutrients in different environments, and then research and design a microcapsule with intelligent response characteristics. Based on external stimuli such as temperature and humidity changes, these intelligent systems can automatically adjust the release rate to ensure that nutrients are released within the optimal time window. In addition, the introduction and application of intelligent materials and control systems, such as the use of temperature sensitive polymers or electronic sensing devices, have elevated the release accuracy and adaptability of microcapsules to a new level, greatly facilitating the intelligent regulation and maximization of nutrient utilization.

5. Conclusion and Prospect

The embedding and release of nutrients in baked goods can be greatly enhanced by microcapsule technology. The basic ideas, methods of preparation, and influencing factors of microcapsule technology during the baking process are examined and studied in this paper, which also suggests several targeted optimization strategies. This study demonstrates that enhancing the stability and release efficiency of nutrient-dense ingredients can be achieved through collaborative preparation process optimization, intelligent release system development, and careful management of wall material design and modification. As research in food chemistry continues to improve, microcapsule technology will make baked goods healthier and more nutritious. At the same time, working together across industries and using new technology will give us more ways to use healthy ingredients in smart and personalized ways, and it will also lead to new ways to use them.

References

[1] Bińkowska, W., Szpicer, A., Stelmasiak, A., Wojtasik-Kalinowska, I., & Półtorak, A. (2024). Utilization of Microencapsulated Polyphenols to Enhance the Bioactive Compound Content in Whole Grain Bread: Recipe Optimization. Applied Sciences, 14(22), 10156.

[2] Vitaglione, P., Troise, A. D., De Prisco, A. C., Mauriello, G. L., Gokmen, V., & Fogliano, V. (2015). Use of microencapsulated ingredients in bakery products: technological and nutritional aspects. In Microencapsulation and microspheres for food applications (pp. 301-311). Academic Press.

[3] Tolve, R., Bianchi, F., Lomuscio, E., Sportiello, L., & Simonato, B. (2022). Current advantages in the application of microencapsulation in functional bread development. Foods, 12(1), 96.

[4] Arepally, D., Reddy, R. S., Goswami, T. K., & Coorey, R. (2022). A review on probiotic microencapsulation and recent advances of their application in bakery products. Food and Bioprocess Technology, 15(8), 1677-1699.

[5] Onwulata, C. I. (2013). Microencapsulation and functional bioactive foods. Journal of Food Processing and Preservation, 37(5), 510-532.

[6] Venturini, L. H., Moreira, T. F. M., da Silva, T. B. V., de Almeida, M. M. C., Francisco, C. R. L., de Oliveira, A., ... & Leimann, F. V. (2019). Partial substitution of margarine by microencapsulated chia seeds oil in the formulation of cookies. Food and Bioprocess Technology, 12(1), 77-87.

[7] Penhasi, A., Reuveni, A., & Baluashvili, I. (2021). Microencapsulation may preserve the viability of probiotic bacteria during a baking process and digestion: A case study with bifidobacterium animalis subsp. lactis in bread. Current microbiology, 78(2), 576-589.

[8] Kumar, L. R., Sanath Kumar, H., Tejpal, C. S., Anas, K. K., Nayak, B. B., Sarika, K., ... & Ravishankar, C. N. (2021). Exploring the physical and quality attributes of muffins incorporated with microencapsulated squalene as a functional food additive. Journal of Food Science and Technology, 58(12), 4674-4684.