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Taste masking using microencapsulation in food and pharmaceutical application

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Abstract

Microencapsulation as a taste masking technique is a well-established technology, especially in both pharmaceutical and functional food industries to increase the consumer acceptability of bitter or unpleasant taste-building ingredients. Microencapsulation techniques encompass many methods such as hot-melt extrusion, coacervation, spray-drying, inclusion complexation, and fluidized bed coating, all of which offer distinct advantages in the taste masking and stability of active compounds. This article discusses key parameters influencing the encapsulation efficiency - polymer concentration, core to shell ratio, curing conditions and applications in drug delivery and nutraceuticals. Microencapsulation is an effective strategy, but has its own limitations associated with available encapsulation materials, regulatory challenges and scale-up issues. Upcoming developments consider sustainable encapsulation products, new methodologies and uses in personal food. Optimising these parameters has great potential in improving the palatability in health-related products.

Keywords: Microencapsulation; Taste Masking; Encapsulation Efficiency; Pharmaceuticals; Food Industry

1. Introduction

In pharmaceutical and food sciences, taste masking is an important practice to enhance the palatability of products that contain bitter active ingredients to facilitate better consumer and patient compliance. Numerous active pharmaceutical ingredients (APIs) are associated with bitter or disfavoured flavours and bitterness in particular, which may cause adherence issues, especially in paediatric and geriatric populations who exhibit greater sensitivity to taste [1, 2]. Taste masking techniques developed by pharmaceutical developers can alleviate or completely mask such undesirable tastes, prompting patients to follow their intended course of therapy [1]. Taste, in humans, is perceived through taste buds, groups of receptor cells clustered together, with a chemical receptor on the end facing the environment to pick up flavor molecules that have escaped into the cell via a tiny surface pore [2].

Common technologies such as microencapsulation are used to keep these bitter APIs from engaging with these taste receptors. This technique involves the coating of individual drug particles with a polymer and/or other materials to offer a barrier for the active pharmaceutical ingredient (API) to come into direct contact with taste buds in the mouth, even when administered as a liquid or chewable modality [2]. It has been successfully applied to hide undesired tastes, especially for formulations developed for specific populations such as children and older people, who have been identified to tend to refuse bitter sensations [2, 5]. These taste receptors can be prevented from interacting with bitter APIs by using methods such as microencapsulation. Such technology involves the coating of individual drug particles with a polymer or other material forming a physical barrier by separating the API from direct contact with taste buds.

Microencapsulation is a versatile technique that extends its applications beyond pharmaceuticals; it is also utilized in the food and agrochemical sectors for the delivery of flavors, vitamins, and oils. Its effectiveness in taste masking stems from its ability to adapt to various compounds and its compatibility with different dosage forms, allowing for broader

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applications in patient-centered formulations [4, 5]. This method not only enhances the patient experience but also addresses a critical objective in both food and pharmaceutical product development, making beneficial yet often bitter ingredients more palatable for a wide range of consumers [4].

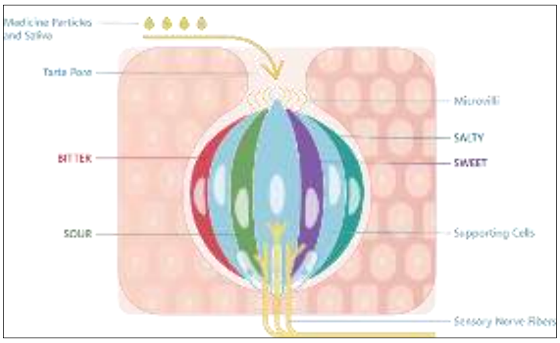

Figure 1 Anatomy of a taste bud [3]

2. Mechanism of Microencapsulation

Microencapsulation operates via several mechanisms, each designed to manage the release and stability of the encapsulated core. The primary structural types include **microcapsules** and **microspheres**. Microcapsules feature a core that houses the active ingredient, encased within a polymer membrane, while microspheres integrate the core uniformly within a polymer matrix [6].

2.1. Wall Materials

The choice of wall material plays a critical role in encapsulation effectiveness, as it must safeguard the core, inhibit undesirable reactions, and be cost-effective. Frequently used wall materials encompass both natural and synthetic polymers such as starch, chitosan, alginate, waxes, and proteins. In many cases, a combination of these materials is employed to deliver optimal protection and controlled release [7].

2.2. Controlled Core Release Mechanisms

The goal of encapsulation is to shield the core from external factors until its release is warranted. Elements such as wall-core interactions, core volatility, wall thickness, and particle size considerably influence the release rate. Several triggers can initiate the release, including:

- **Diffusion**: The core substances spread through an unbroken wall, with the diffusion rate influenced by the chemical and physical characteristics of both the core and wall materials.
- **Degradation**: Enzymes such as proteases or lipases break down the wall material, facilitating controlled release.
- **Solvent Contact**: When exposed to a solvent, the wall material can dissolve, allowing for the release of the core. This process is employed in encapsulated coffee flavors, which are released upon contact with water.
- **pH Changes**: Changes in pH can affect the solubility of the wall, enabling targeted release in specific environments, as seen with probiotics that survive stomach acid and release in the intestine.
- **Temperature Shifts**: Walls sensitive to temperature release their core when heated; this is typical in fat-encapsulated flavors used in microwave popcorn, where the core is released as the temperature reaches a certain level.

These mechanisms enhance the versatility of microencapsulation in safeguarding, stabilizing, and regulating the release of various active ingredients in both food and pharmaceutical contexts [8, 28].

3. Coating Materials

The material used for coating or wall construction in microencapsulation is vital for taste masking, as it creates a cohesive film around the core substance. This film strengthens the capsules while remaining chemically inert to prevent any interactions with the core ingredients, thus avoiding undesirable flavors. An effective coating material should also be impermeable, allowing for the controlled release of the core contents at designated times and locations under specific conditions. Commonly utilized materials include proteins (such as gelatin), polysaccharides (like alginate and chitosan), and lipids (fats and waxes), each possessing distinct properties that can be customized for optimal performance in safeguarding flavors or probiotics. The selection of the coating material is essential, as it significantly impacts the effectiveness of taste masking, the stability of the product, and the delivery of active components in both food and pharmaceutical applications [24].

Table 1 Coating materials, sources, properties, and suitable techniques microencapsulation [20]

Coating Material	Source	Properties	Technique Used
Gums	Gum Arabic, sodium alginate, Carrageenan	Form soft elastic gels, poor tensile strength, hydrocolloidal	Extrusion, phase separation Spray drying, coacervation, emulsification
Carbohydrates	Starch, dextran, sucrose	Hydrocolloidal, comparatively higher tensile strength than gums	Spray drying, fluidized bed coating, extrusion, freeze drying
Proteins	Gelatin, albumin	Emulsification, gelation, foaming, and water binding capacity	Spray drying, extrusion, coacervation, freeze drying emulsification
Lipids	Bees wax, stearic acid, Phospholipids	Plasticizing properties, Good barrier to gases and water vapor	Fluidized bed coating, spray chilling/cooling, extrusion
Cellulose and their derivatives	Plant cells	Hydrophilic, good film forming ability and surface activity	Spray drying, fluidized bed coating, extrusion, emulsification/precipitation Coacervation
Chitosan	Shells of crustaceans	Good barrier to gases and water vapor	Spray drying, coacervation, emulsification

4. Microencapsulation in Food Industry and Pharmaceuticals

4.1. Microencapsulation in Food Industry

The food industry is increasingly adopting microencapsulation techniques to safeguard complex ingredients such as probiotics in fermented meats, polyunsaturated fats in dairy, and volatile flavors in instant foods. This method not only maintains the taste and stability of nutrients but also enhances health benefits—for example, by integrating calcium to help prevent osteoporosis, utilizing lactic acid from probiotics to lower cholesterol levels, and incorporating phenolic compounds to support heart health [6].

The applications and benefits of microencapsulation in the food sector have been thoroughly researched. It provides various advantages, including:

- Protecting sensitive active compounds from environmental elements like light, heat, and oxygen.
- Shielding volatile compounds to prevent evaporation.
- Masking undesirable tastes and odors.
- Converting liquids into solid forms for easier handling.
- Enhancing the solubility of compounds that are otherwise poorly soluble.
- Enabling targeted delivery and controlled release of active ingredients.
- Improving the effectiveness of bioactive compounds by preserving their stability and activity.

These applications make microencapsulation an invaluable tool in creating stable, palatable, and effective food products [9,12].

4.2. Microencapsulation in Pharmaceuticals

Microencapsulation is a well-established technology in the pharmaceutical sector, with taste-masking emerging as a significant application area. Essentially, microencapsulation allows for the encapsulation of bitter active ingredients, thereby preventing their interaction with taste buds [1]. This technique can be utilized to mask the bitter flavors of drugs and involves microencapsulating drug particles using various coating agents. Commonly used coating agents include gelatin, povidone, HPMC, ethyl cellulose, beeswax, carnauba wax, acrylics, and shellac [13].

Taste-masking methods are crucial for enhancing the palatability of medications, particularly in formulations for children and the elderly. The importance of these techniques has grown alongside the emergence of fast-dissolving tablets. Many drugs exhibit bitterness when dissolved in saliva and come into contact with taste buds, and those with high solubility in saliva typically have a more pronounced unpleasant taste [17].

The application of microencapsulation in the pharmaceutical industry has been extensively researched, revealing several benefits, including:

- Prolonged-Release Dosage Forms: Microencapsulation is particularly useful in formulating tablets, capsules, or injectables for extended release, allowing the drug to be released gradually over time.
- Enteric-Coated Dosage Forms: It enables targeted release in the intestines rather than the stomach, protecting the active ingredient from stomach acids and reducing gastric irritation.
- Taste Masking: Microencapsulation is effective in masking the taste of bitter drugs, improving patient compliance.
- Oily Drug Addition in Tablets: By encapsulating oily medications, microencapsulation aids in tablet formulation, reducing issues with tacky textures that can disrupt tablet production.
- Protection from Environmental Hazards: It provides a degree of protection from moisture, light, oxygen, and heat, extending the shelf life of sensitive drugs.
- Separation of Incompatible Substances: Incompatible ingredients can be encapsulated separately to prevent adverse reactions, such as liquid formation, ensuring the stability of the final product.
- Safe Handling of Toxic Substances: Microencapsulation reduces the dangers associated with handling toxic or hazardous materials, like fumigants and pesticides, by containing them within a protective layer.
- Reduced Hygroscopicity: Encapsulation minimizes the moisture absorption of hygroscopic materials, helping maintain their stability and effectiveness.
- Reduced Gastric Irritation: Encapsulated drugs are gentler on the stomach, as the coating can prevent irritation by controlling the release location.

These applications demonstrate the versatility of microencapsulation in improving drug stability, safety, and patient comfort [10, 11, 15].

5. Different Techniques of Microencapsulation for Taste Masking

5.1. Hot-Melt Extrusion (HME)

Hot-melt extrusion (HME) is an advanced method for taste-masking that is highly regarded for its efficiency and potential in pharmaceutical applications. Unlike conventional techniques, HME does not require organic solvents, minimizes the number of processing steps, allows for continuous operation, and can be easily scaled for larger production needs [1]. In this process, a bitter active ingredient is blended dry with other excipients and then loaded into a hopper, which feeds the mixture into an extruder. Through the application of heat and intense shear mixing, the materials are melted and combined to create a taste-masked extrudate. Once formed, this extrudate can be milled or micronized to produce taste masked granules or fine particles suitable for various dosage forms, such as tablets or capsules. Twin-screw extruders are frequently employed in HME due to their benefits, including high shear kneading, efficient material feeding, shorter transit times, and reduced risk of overheating, making them particularly ideal for processing sensitive compounds [1, 2].

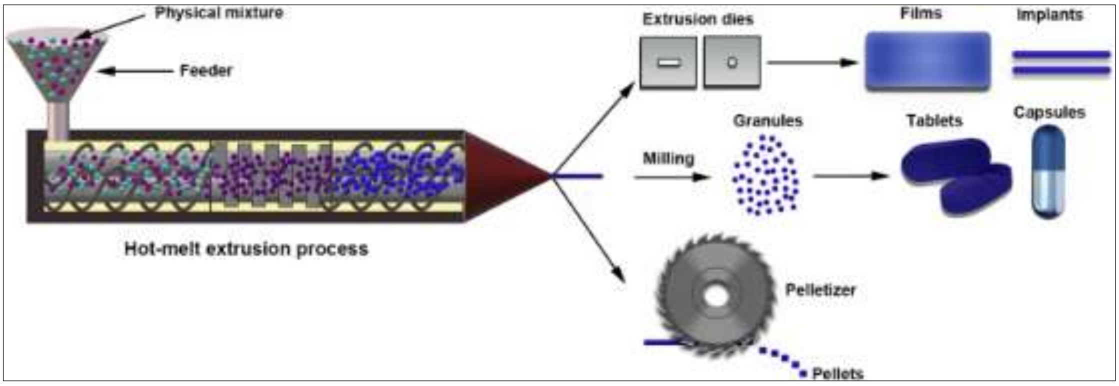

Figure 2 Hot Melt Extrusion [21]

5.2. Coacervation

The Coacervation method is a widely recognized microencapsulation technique utilized for taste masking, achieved by forming a protective coating around bitter drug molecules. This process has three main steps:

- Formation of Immiscible Phases: This process involves preparing three distinct phases: a liquid manufacturing phase, a core phase that contains the drug, and a coating phase that includes the encapsulating material.
- Polymer Coating Deposition: In this step, the coating material, typically a liquid polymer, envelops the core material. This occurs at the interface between the core and the surrounding liquid, facilitating the encapsulation process.
- Solidification of the Coating: The coating is solidified through techniques such as thermal treatment, cross-linking, or desolvation, resulting in stable microcapsules [18].

This method presents several advantages, including high encapsulation efficiency (90%), avoidance of high temperatures, and elimination of organic solvents, making it ideal for thermosensitive drugs. However, the use of specific crosslinkers, such as glutaraldehyde, can restrict its applications in the food industry. An example of coacervation can be seen in the encapsulation of capsaicin, the active component in hot peppers, which is applied in food flavoring to help control its potent taste and release [9, 16, 18, 19].

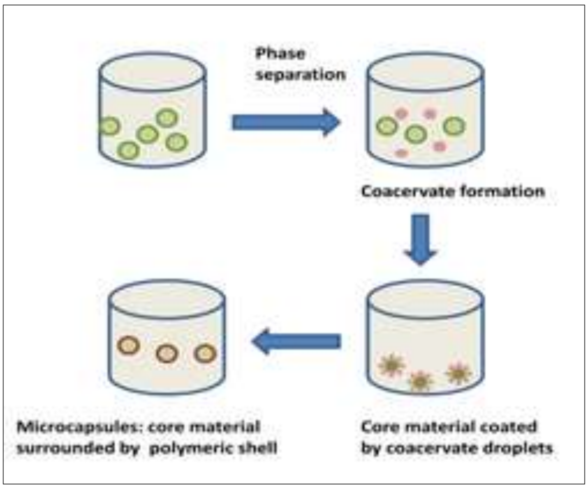

Figure 3 Coacervation [20]

5.3. Spray-Drying

Spray drying provides an alternative method for taste-masking by employing a physical barrier coating. The bitter drug is either dissolved or dispersed with the polymer in an appropriate solvent, followed by spray-drying. This process involves three main steps:

- Atomizing the feed into a spray

- Allowing spray-air contact followed by drying
- Separating the dried product from the air

The method allows for the use of both aqueous and non-aqueous solvents. The resulting dried product typically consists of granules or beads that contain taste-masked encapsulated drugs. The thickness of the polymer coating can sometimes hinder drug release, necessitating careful selection of the polymer and design of the process to achieve effective taste-masking [23, 29].

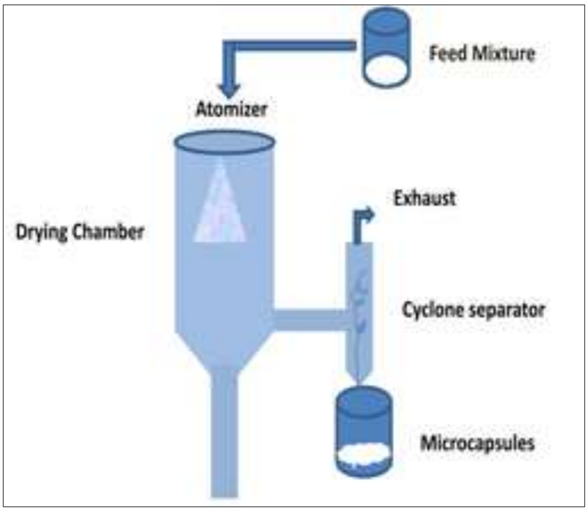

Figure 4 Spray dray [20]

5.4. Inclusion Complexation

Inclusion complexation is a microencapsulation technique for taste masking that functions by trapping the drug molecule within the voids of a complexing agent, thereby preventing direct contact with taste buds and reducing sensitivity to bitterness. Cyclodextrins, which are cyclic oligosaccharides derived from starch, are used as complexing agents due to their non-toxic, hydrophilic exterior and hydrophobic cavity. This unique structure enables cyclodextrins to encapsulate a wide variety of substances including solid, liquid or gas form.

Among them, β-cyclodextrin (β-CD) is often favored due to its cost-effectiveness and ease of production. Research has shown that β-CD is effective in taste-masking applications, such as in cetirizine-based chewing gum, which demonstrated improved drug release and taste masking through inclusion complexes [14].

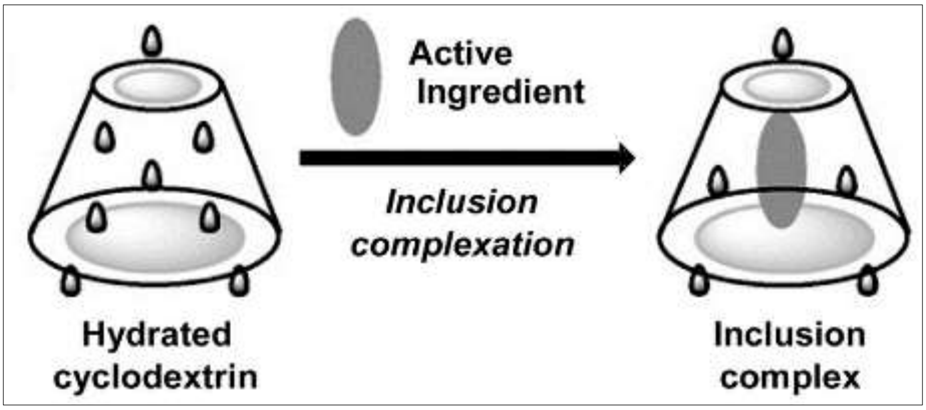

Figure 5 Inclusion complexation [22]

5.5. Fluidized Bed Coating

Fluidized bed coating is a notable microencapsulation technique for taste masking, as it enables precise application of film coatings and binders on various particulate materials. This method offers the flexibility to create functional coatings and control thickness to meet specific requirements. In this process, solid particles are suspended in a chamber with controlled airflow, allowing the coating material to adhere to the surface of each particle. As the particles are mixed with air, they form a circulating flow that ensures uniform coating without agglomeration and facilitates a rapid drying rate. Wall materials such as starch, cellulose derivatives, proteins, and dextrin form a film around the core, effectively masking unpleasant tastes by preventing direct contact with taste buds [36].

It was previously developed as a pharmaceutical technique, but it is now increasingly being applied in the food industry to tune the effect of functional ingredients and additives. Fluidized bed encapsulation is versatile and used extensively for food additives like acids (lactic, citric, ascorbic) and leavening agents, as well as in probiotics, where it improves stability and controlled release, effectively concealing bitterness in various applications [9].

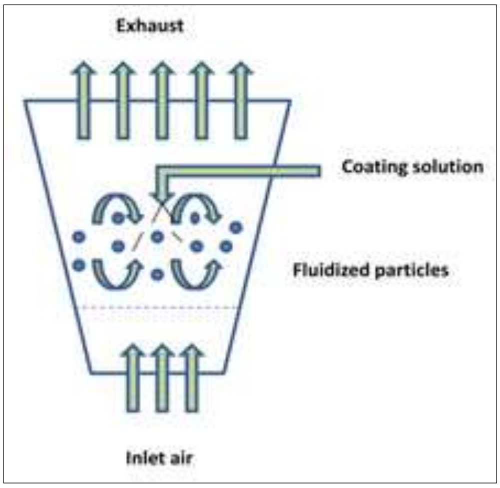

Figure 6 Fluidized bed coating [20]

6. Factors Influencing Microencapsulation

The encapsulation efficiency of microparticles, microcapsules, or microspheres is influenced by various parameters. Encapsulation efficiency is defined as the ratio of the amount of core material encapsulated within a wall material to the concentration of the core material used for encapsulation via a specific technique. This efficiency is dependent on the concentration of the core material employed during the encapsulation process [39].

Several factors influence the effectiveness of microencapsulation techniques for taste masking, which are crucial for ensuring the stability and delivery of active ingredients. Key factors include:

- Polymer Concentration: The concentration of the polymer utilized can greatly influence the efficiency of encapsulation. While higher concentrations may improve barrier properties, they can also increase viscosity, which can impact the dynamics of the process [25].
- Polymer Solubility: The solubility of the polymer in the selected solvent is crucial. Insufficient solubility can impede the formation of a uniform coating, which may affect the success of encapsulation [26].
- Solvent Removal Rate: The rate at which the solvent is removed during the microencapsulation process can influence the formation and stability of the microcapsules. A controlled removal rate is essential for achieving optimal encapsulation results.
- Organic Solvent Solubility: The solubility of organic solvents in water can also play a significant role in encapsulation efficiency, especially in processes involving phase separation [27].
- Shell Material Concentration: Comparable to polymer concentration, the concentration of the shell material impacts microcapsule performance. Finding an optimal balance is necessary to ensure effective taste masking. The ratio of core to shell material is critical, as it determines both the release dynamics and the level of protection of the active ingredient.
- Core/Shell Ratio: The ratio of core material to shell material is critical, as it determines the release dynamics and the protection level of the active ingredient.
- Emulsifying Technology: The methods used for emulsification can impact the homogeneity and stability of the microcapsules, directly affecting their performance.

- Curing Conditions: The conditions under which the microcapsules are cured (e.g., temperature, time, and environment) also play a vital role in determining the structural integrity and functionality of the microcapsules [30].

These factors must be carefully optimized to enhance the efficiency of taste masking in various applications, particularly in food and pharmaceuticals.

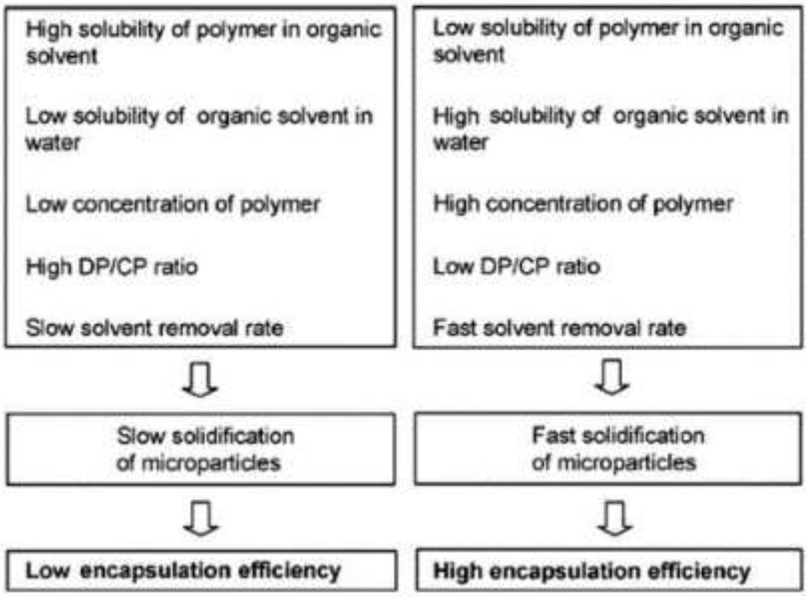

Figure 7 Factors influencing the encapsulation efficiency [31]

7. Applications of Microencapsulation in Taste Masking

Microencapsulation has emerged as a promising technique for taste masking, particularly for bitter drugs, significantly enhancing the quality of treatment for patients, especially children and also in the field of nutraceuticals and functional food. This method involves enclosing the particle in a protective coating, which helps to prevent the release of the bitter taste until it reaches the desired site of action in the gastrointestinal tract, showing significant promise in both the pharmaceutical and functional food nutraceutical industries.

7.1. Pharmaceutical Applications

In the pharmaceutical sector, microencapsulation is primarily used to mask the bitter taste of drugs, particularly those intended for children. By enclosing the active pharmaceutical ingredients (APIs) within a protective coating, microencapsulation prevents the release of undesirable flavors until the medication reaches the gastrointestinal tract. This method not only improves patient compliance but also enhances the overall treatment experience, making it more palatable [35]. Additionally, research continues to explore various formulations and encapsulation techniques to enhance the efficacy and stability of taste-masked drugs [27].

7.2. Functional Food and Nutraceutical Applications

Microencapsulation in food and nutraceutical literature highlights the importance of enhancing product appeal. this technique successfully hide bitter, off-flavors from functional foods and makes it possible to enrich the functional foods with vitamins, minerals and other bioactive compounds without affecting overall taste profile. That is, things like omega-3 fatty acids, which are good for you but taste gross, can be encapsulated very well to make people actually eat them. In addition, microencapsulation can provide stability for sensitive ingredients like probiotics and controlled release for foods like energy bars and beverages [33, 34].

In summary, microencapsulation is a multipurpose and efficient taste masking technique in both pharmaceuticals and food/nutraceuticals. Boosting flavor profiles, increasing ingredient stability, providing controlled release, this technology has aided in the making of more palatable and efficient products in many industries [44].

Figure 8 Advantages of Flavour microencapsulation in chewing gums [14]

8. Evaluation of Taste Masking Effect

Evaluating the effectiveness of taste masking is crucial in the formulation of products, especially pharmaceuticals. Sensory analysis, which assesses flavors and scents, has evolved from relying solely on expert subjective comparisons to incorporating both objective and subjective methods.

Taste perception is highly subjective, varying among individuals. To quantitatively assess taste sensation, several methods have been documented in the literature, including:

- **Multichannel Taste Sensors:** These devices, such as those developed by Sotakagi et al., mimic human taste perception by converting taste information into electrical signal patterns. They can quantify the suppression of bitterness in substances like Quinine when combined with sugar [32].
- **Rate of Drug Release:** One effective way to assess taste masking is by measuring the rate of drug release from coated microspheres. A slower release rate typically indicates better taste masking. Similarly, using ion exchange resins, the drug release rate serves as a measure of taste masking effectiveness [27].
- **Trained Panel Testing**: A trained taste panel consisting of 5–10 healthy volunteers can provide qualitative assessments of taste stimuli through panel testing.
- **Frog Taste Nerve Responses:** In this method, the glossopharyngeal nerve of anaesthetised adult bullfrogs is dissected and analysed using an AC amplifier. The peak response height indicates taste sensitivity.
- **Spectrophotometric Evaluation**: This technique involves mixing a known quantity of the formulation with 10 ml of distilled water and filtering the mixture. The drug concentration in the filtrate is then determined spectrophotometrically. If this concentration is below a specific threshold, it suggests effective taste masking [34].
- **Time-Intensity Approach:** In this method, a sample is held in the mouth for 10 seconds to immediately record bitterness levels, providing a quantitative measure of taste sensation.

These methods collectively enhance the understanding and measurement of taste masking effectiveness, offering a comprehensive approach to evaluate how well a formulation can mask undesirable tastes [34].

9. Challenges and Limitations of Microencapsulation Technique

Microencapsulation for taste masking, while highly beneficial in pharmaceutical and food applications, faces distinct challenges and limitations. One primary difficulty lies in selecting optimal preparation conditions to ensure effective encapsulation, as quality and functionality are heavily influenced by the chosen techniques, core materials, and wall materials, consumer preferences in the food industry, such as gluten-free, lactose-free, and low-sugar options, require encapsulation materials that not only meet dietary restrictions but also maintain safety and efficacy [37, 38, 40].

A limited selection of approved encapsulating materials suitable for food applications. Plant-based materials like pea, soy, and wheat proteins are increasingly preferred over animal-based options due to regulatory pressures and growing consumer demand for non-animal alternatives. However, plant proteins may lack the strength and stability provided by synthetic or animal-derived polymers, impacting the effectiveness of taste masking [42].

In both food and pharmaceuticals there is an emphasis on "clean-label" ingredients, which restricts the use of synthetic polymers often required in pharmaceuticals. Further, the process is sensitive to variables like temperature, pH, and solvent compatibility, all of which can affect the stability and performance of the encapsulation. For instance, exposure to high temperatures can degrade heat-sensitive compounds, while certain solvents may compromise the encapsulating wall [43].

Controlled release for effective significant obstacles as well. For taste masking to be successful, the encapsulation must withstand varying pH levels and enzymatic environments until the compound reaches its intended site of release. Additionally, scaling up production in a cost-effective manner presents a considerable limitation, as developing regulatory-compliant, affordable solutions for nutraceuticals and food products often increases production costs [45, 46, 47].

10. Future Perspective and Innovation

Further developments in microencapsulation for taste masking is likely to provide huge space for innovation, particularly considering consumer needs and regulatory expectations evolve. Microencapsulation: An Established Technology That Was Once Groundbreaking (and still holds promise) across different sectors, it is still underutilized in food and nutraceuticals industries — wherever a taste masking is important. A key area of the future is to sustain its growth, with limited synthetic polymers, and move toward plant-based, clean-label. Options such as pea, soy and other plant proteins are on the rise. Despite the widespread acceptance of these materials, greater scientific research is needed to determine the stability and efficacy of conventional encapsulants, especially for aroma compounds and bioactives. By-products such as proteins derived from food waste provide an additional potential path for encapsulants, allowing the food industry to reduce waste while enhancing encapsulation technology [41, 53].

Spray drying remains the most common microencapsulation method due to its cost-effectiveness and versatility. However, research is advancing to refine spray drying and explore innovative methods like supercritical fluid encapsulation and electrospraying. These techniques aim to improve encapsulation precision, controlled release, and stability of sensitive ingredients, such as vitamins and flavoring agents, even in complex products like confectionery [48, 49, 50].

Looking forward, microencapsulation in the food industry is expected to focus on sustainability, precision, and personalized nutrition. This includes using natural, plant-based encapsulants to meet clean-label and regulatory requirements and leveraging advanced techniques like electrospinning and 3D printing for multi-layered encapsulation and controlled release. Personalized nutrition is likely to benefit from microencapsulation's ability to deliver nutrients tailored to individual needs, while smart packaging and nanoencapsulation offer new ways to preserve quality and improve nutrient bioavailability [51, 52].

However, eco-friendly production still proves to be challenging for industrial application and methods are being developed. Regulatory standards will be a continued influence on the future of encapsulation innovation, facilitating cross-sector collaboration to ensure innovations are commercially viable and safe for consumers. Microencapsulation for taste masking will be driven by sustainable, compliant, more potent encapsulation techniques and better materials that support large scale production and high quality, consumer quality formulations [54].

11. Conclusion

Microencapsulation has revolutionised taste masking in both the pharmaceutical and functional food sectors, effectively masking undesirable flavours and enhancing consumer acceptance. In pharmaceuticals, it improves treatment compliance by minimising the bitterness of active ingredients, especially for children and the elderly. Similarly, in nutraceuticals, it allows for the inclusion of bioactive compounds without compromising taste.

Despite its advantages, challenges remain, including limited encapsulant materials, stability under varying conditions, and the need for clean-label ingredients. Additionally, the scalability and cost-effectiveness of production must be addressed to transition from lab-scale to industrial applications.

Future innovations are directed at refining encapsulation techniques, exploring sustainable and plant-based materials, and improving the stability and controlled release properties of encapsulated compounds. Techniques like supercritical fluid encapsulation and electrospraying show promise for more efficient and precise applications, potentially enhancing the encapsulation of sensitive compounds in more complex formulations. With continued research and cross-disciplinary collaboration, microencapsulation technology can be optimised to meet the evolving demands of both consumers and regulatory bodies, ultimately advancing the field and fostering the development of high-quality, consumer-friendly health products across industries.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare no conflict of interest.

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