

Spirits to Confections: Advances in Alcohol Encapsulation and Edible Delivery Systems : A Review

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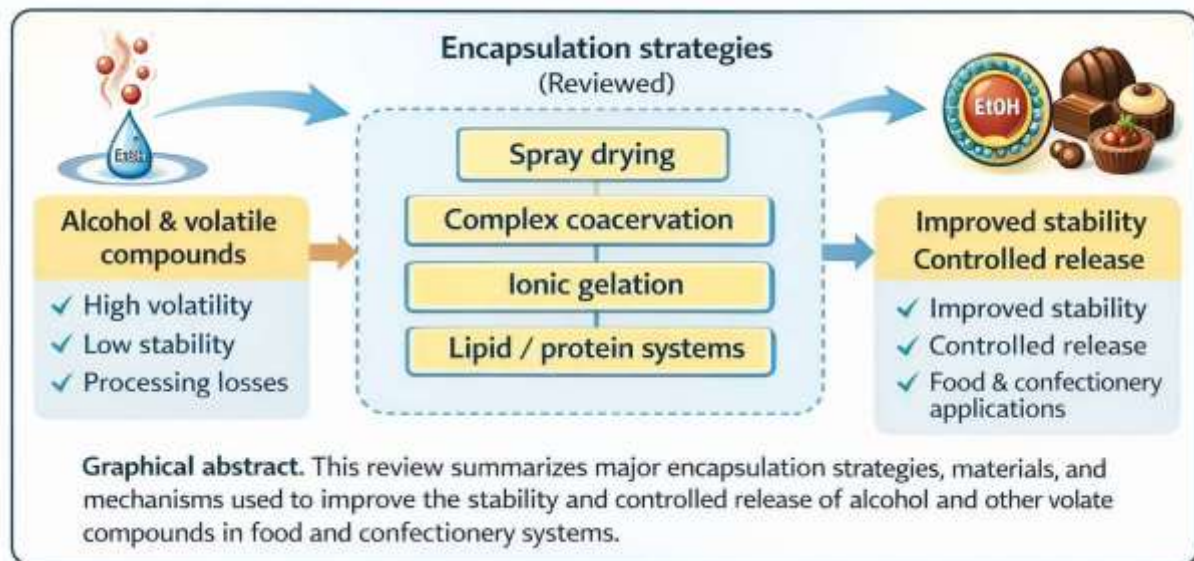
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Abstract

An increasingly common method for improving the stability, controllability, and while the sensory components of volatile alcohols (esters) are retained in sweets is to enclose them in alcohol. The inherent volatility and sensitivity of alcohols to changes in They pose challenges when directly included into food systems due to temperature and chemical interactions. However, by employing encapsulation techniques, we can preserve the alcoholic components and utilise them throughout processing and storage without losing any of their efficacy. Additionally examine how well encapsulated alcohols hold up in various food systems, including those used in baking, confectionery, and gelled foods. Present food-grade encapsulation methods and their limitations in controlling the delivery of encapsulated alcohols will be outlined. Also shown and assessed for the future are the most important areas of research that need to be filled in order to develop encapsulation technologies that are both effective and acceptable to consumers. Some of the methods used to encapsulate alcoholic compounds used in confectionery include spray drying, complex coacervation, ionic gelation, nanoencapsulation, microfluidics, and layer-by-layer assembly. The review will also provide a critical assessment of these methods. they examine several wall materials (including carbs, proteins, lipids, and polymers) as encapsulation matrix for alcohol components; also, the encapsulation efficiency, performance, and physicochemical properties of alcohols.

Keywords: Alcohol encapsulation, encapsulation materials, food-grade delivery systems, microencapsulation, confectionery applications.

Figure 1: Methods for encapsulating alcoholic beverages to make them more stable and to regulate their release in food



1. Introduction

There is a wide variety of alcoholic chemicals that are used in cooking to give foods their signature scent, flavour, and sensory challenge. But alcoholic compounds' reduced heat of combustion, propensity for evaporation and oxidation, and high volatility make them unsuitable for use in baking and confectionery. Physicochemical characteristics, in general, cause the loss of substantial quantities, taste inconsistency, and instability when added directly to the foods (Perry and McClements 2020). However, encapsulation has emerged as an increasingly investigated technology aimed at overcoming these constraints by encapsulating the alcohol physically in a protective matrix. (Desai and Park 2005; Madene et al. 2006). The encapsulated alcohols exhibit improved retention during processing and controlled release during consumption, resulting in enhanced product consistency (Estevinho et al. 2024).

Confectionery materials can be effectively protected from volatile losses using combinations of substances that are suitable for use in food, such as carbs, proteins, lipids, biopolymers, all of which remain compatible. Recent technological breakthroughs in encapsulation methods such as spray drying, complex coacervation, ion gelation, and nanoscale delivery systems allow for better encapsulation efficiencies and control of kinetic release (Gouin 2004; Zuidam and Shimoni 2010; Augustin et al. 2015; Subramani et al. 2020; English et al. 2023).

Nevertheless, Concerning micro- and nanoscale delivery, there are ongoing limitations and difficulties with encapsulating approaches that relate to regulatory approval and cost-effectiveness. alcohol encapsulation in food systems works, the methods employed, and the materials that work best for candies are all covered in this article. This study aims to summarise existing methodologies in a clear and comprehensive manner, point out important limits, and propose future approaches that are related to basic concerns in food science and engineering.

2. Fundamentals of Alcohol Encapsulation

2.1 Physicochemical Properties of Alcohol Cores

Hydrophilicity, polarity, molecular weight, and volatility are some of the physicochemical properties of alcohols that significantly impact their encapsulation potential. Heating aromatics and alcohols causes

them to evaporate and oxidise more quickly than other substances due to their low boiling temperatures and high vapour pressure (Madene et al. 2006). To do this, one must select an encapsulating material that can securely serve as a robust diffusion barrier, thus avoiding material loss caused by volatilisation. Alcohols' polarity and water miscibility impact their interactions with matrix molecules such as carbohydrate complexes, proteins, arabic gum, maltodextrin, While crystalline matrices have been shown to retain volatile alcohols better than the amorphous carbohydrate matrix, this may be due to easier diffusion or less loss of a compound (Shiga et al. 2014). On top of that, surfactants and emulsifiers such as lecithin or sodium lauryl sulfate have been shown to increase the stability of the emulsion system and the encapsulation process (Encina et al. 2018).

2.2 Release Mechanisms and Kinetics

Alcohol evaporates from water's surface when exposed to it. Fickian diffusion then allows it to disperse into the environment. Consequently, diffusion is the principal mode of transport in these systems (Encina et al. 2018). Efficient and effective release of sensory characteristics requires optimisation of these systems for sweets. To accomplish this, systems with well-balanced retention and release characteristics are required.

Encapsulation Efficiency and Stability

Encapsulation efficiency (EE) is a significant determinant for alcohol retention by encapsulation and is typically quantified as a ratio between the amount of alcohol that is entrapped and the total amount that was encapsulated (Gharsallaoui et al., 2007). Optimal encapsulation efficiency leads to reduced volatilization losses and optimised sensory attributes within the final food product (Encina et al., 2018). For alcohol encapsulation matrices, encapsulation efficiency can be influenced by the nature of core-wall interactions and the shape of the particle (Gharsallaoui et al., 2007; Encina et al., 2018). A significant aspect of carbohydrates, particularly carbohydrate-based matrices such as maltodextrin and gum arabic, is that they have demonstrated reliable encapsulation efficiencies in excess of 80% following spray drying under optimized conditions, especially when produced in an amorphous state (Lee et al. 1999; Jafari et al. 2008).

While protein-based delivery systems such as whey protein isolate and casein may provide even greater encapsulation efficiency than carbohydrate-based matrices due to their natural propensity to have affinity for interfaces and their capacity to strongly adsorb to interfaces, permitting a higher degree of alcohol retention (Charve and Rousseau 2009). Lipid-based carriers like solid nanoparticles and nanoliposomes would further increase the encapsulation efficiency by entrapping the alcohol molecules either physicochemically or within their hydrophobic matrices (Fathi et al. 2012). If the carrier system is resistant to temperature, oxygen, moisture, and tensile tension, then the encapsulated alcohol will remain stable. By lowering the mobility and diffusibility of volatile chemicals, encapsulation matrices with low hygroscopicity and high glass transition temperatures typically show increased shelf-life stability (Gharsallaoui et al. 2007). Alternatively, with high relative humidity, a hygroscopic system may exhibit structural relaxation and activate alcohol migration. Confectionery and pastry products face the added challenge of processing stability because to the potential for higher temperatures to result in substantial alcohol loss. Multiple experimental investigations have demonstrated that, when subjected to mild heating, encapsulation systems may keep over 80% of the alcohol content, while unencapsulated systems are able to retain less than 50%. (Tolve et al. 2022). To successfully incorporate alcohol into the food system, it is crucial to optimise encapsulation mechanisms.

Interaction of Alcohol with Encapsulation Matrices

How well an alcohol core interacts with the encapsulation matrix is a major factor in how well the encapsulation works and how the release goes. Van der Waals forces, electrostatic attraction, hydrogen bonding, hydrophobic interaction are the primary intermolecular interactions that drive the interaction between alcohols and matrices. All these are responsible for influencing stability and retention of alcohol in the carrier system, as explained by Perry and McClements (2020).

Since all three forms of carbohydrate— starch that has been modified, gum arabic, and maltodextrin— share all of their physical qualities, the predominant bonding between these carbs is hydrogen rather than chemical bonding. The amorphous state of carbohydrate carriers will decrease the movement of molecules and will therefore have an effect on the rate of diffusion of alcohol. Carbohydrate carriers in crystalline form may favor the separation of phase and volatilization because of lower barrier properties (Shiga et al. 2014). The extent of polymerization as well as the glass transition temperature of the carbohydrate carrier also affects the retention of alcohol. (McClements 2018).

Due to proteins' amphiphilic nature, protein-based encapsulation systems exhibit strong contact forces when combined with alcohol and matrices. Proteins like whey protein isolate, casein, or gelatin have the potential to adsorb at the interface in alcoholic systems, creating viscoelastic interfacial layers to improve the stability as well as the efficiency of encapsulation (Charve and Rousseau 2009). Alcohol-induced protein denaturative unfolding can result in the creation of hydrophobic regions, thus promoting core retention in addition to the effect during the aqueous or thermal treatment phases (Zhong et al. 2023).

Alcohol interacts with lipid-based delivery techniques primarily through hydrophobic partitioning, which is on the basis of solid lipid cores or lipid bilayers.

Nanoliposomes, solid lipid nanoparticles, and lipid-based nanostructured carriers can restrict the diffusion of alcohol by forming lipid domains that result in a strong barrier against evaporation and oxidation (Fathi et al. 2012). Because of the potential interference with the lipid arrangement caused by high alcohol concentrations, it is important to employ an ideal composition ratio. When it comes to encapsulation technologies, the utilisation The effects of combining carbohydrates, proteins, and lipids are usually quite synergistic. Electrostatically bonded protein-polysaccharide complexes offer strong capsules that can withstand various stresses and are ideal for use in the production of confectionery products that require control and heat resistance in their release (English et al. 2023).

2.3. Encapsulation Technologies

To better retain alcohol in food systems and manage its release, several encapsulation technologies have been developed. Processing circumstances, maximise the effectiveness of encapsulation, control the release behaviour, and ensure compatibility with sweet matrices are all factors to consider when choosing a suitable method.

Spray Drying

The spray drying process is widely utilised in the food sector for encapsulation because it is scalable, cost-effective, and can be applied to materials that are suitable for consumption. Spray drying involves the atomization of alcoholic emulsions with wall materials like maltodextrin, gum arabic, or hydroxypropyl starch in a heat stream, so that rapid evaporation of the solvent takes place, thereby producing microcapsules (Gouin 2004; Reineccius 2004; Gharsallaoui et al. 2007). More than 80% encapsulation has been achieved for ethanol and volatiles with amorphous carrier matrices with proper emulsifiers (Lee et al. 1999). Alcohol retention is greatly affected by the primary processing parameters,

which include emulsion stability, solid concentration in the feed solution, air intake and exit temperatures, and other similar factors. Even though alcohol systems are susceptible to high temperatures, this technology is ideal for spray drying because of its quick drying period, which allows for high temperatures to be avoided in the process. Alcohol can also be lost by diffusion and localisation. (Soottitawat et al. 2003).

Complex Coacervation

The alcoholic core is encased in a polymer-rich phase by complicated coacervation, which relies on interactions involving electrostatic fields between biopolymers, such as polysaccharides and proteins that have opposite charges. Wang et al. (2018) reported that under mild processing conditions, protein/polysaccharide mixes, such as whey protein-gum arabic or gelatin and chitosan mixtures, were able to achieve encapsulation efficiencies for volatile chemicals over 85%. The method's controlled release characteristics and high core loading capabilities are two of the numerous advantages of encapsulation, while the efficiency of the process depends on pH, concentration, and ratio. The intrinsic intricacy of this technology makes wider adoption problematic, despite its various favourable uses.

Ionic Gelation

The process of ionic gelation involves cross-linking polyelectrolytes, calcium ions and other multivalent cations are commonly found in sodium alginate in order to create a low-temperature encapsulating medium.

Alcohol-containing alginate solutions form hydrogel beads upon contact with calcium salts, entrapping the alcohol within a hydrated polymer network (Patil and Paradkar 2006). The encapsulation efficiency varies from 70% to 95%, depending on the formulation conditions (Guerra-Valle et al. 2022). Systems based on alcohol that are sensitive to heat and confectionary items based on gels are the best candidates for this technology. It may not be suitable for usage in dry sweets due to its hygroscopic properties and greater particle size.

Nanoencapsulation Approaches

Techniques of nanoencapsulation such as nanoemulsions, nanoliposomes, and solid lipid nanoparticles ensure better protection and release characteristics of alcohol because of the minimized diffusion distances and enhanced interface stabilization (Fathi et al. 2012; Assadpour and Jafari 2018). When essential oils are nanoencapsulated, their molecular protection efficacy exceeds 85%. Despite their many advantages, nanoencapsulation techniques are typically associated with expensive machinery, which limits their use to only high-quality food products. Additionally, some aspects of regulations regarding nanomaterials require a comprehensive evaluation. (Bakry et al. 2016).

Emerging Technologies

Capsule size and release rate can now be precisely controlled thanks to new developments in microfluidic manufacturing and layer-by-layer assembly techniques. Microfluidic methods have made it possible to create monodisperse particles, and layer-by-layer assembly methods make it possible to assemble multi-layer capsules and control their permeability (English et al. 2023). Although there is a throughput limitation, the results show promise.

2.4 Encapsulation Materials

The parameters of alcohol retention and release are significantly impacted by the materials used for encapsulation. To be considered food-grade, encapsulants must be physicochemically stable, sensory-neutral, and efficient against volatilisation.

Carbohydrate-Based Materials

Carbohydrates are a popular choice for food encapsulation wall materials because of their solubilisation and film-forming properties. The alcoholic fraction is often encapsulated in spray-dried encapsulation ways in which the wall components are composed of starches that have been changed, gum arabic, or maltodextrin. Maltodextrin is used to provide strength and low hygroscopy, but its most important use is in providing friendly emulsifying properties, which improve the retention of the alcoholic fraction in mixed matrices (Gharsallaoui et al. 2007).

Encapsulation efficiencies of more than 80% have been reported in alcohol-based formulations with optimized maltodextrin and gum arabic formulations, particularly in the preparation of amorphous matrices (Lee et al. 1999; Siccama et al. 2021). Matrix viscosity and rigidity can be enhanced by using modified starch or cellulose derivatives, among other substances. This way, the mixture stays stable and you get a more controlled release in candies (Jaric et al. 2024).

Protein-Based Materials

Alkaloid emulsifiers or stabilisers derived from whey protein isolate or concentrate, casein, or gelatin mixed with ethanol (e.g., whiskey) help form a barrier around the core material (Charve & Rousseau, 2009). When proteins unfold, hydrophobic regions of the molecule become visible, which help to keep the core in place. Systems based on proteins are more effective at encasing the core and preventing oxidation than carbohydrate-based systems with identical compositions.

The mechanical properties and thermal/environmental stability of the chemically and electrostatically derived protein- polysaccharide complexes formed from electrostatic interactions allow these complexes to provide a strong shell and exhibit improved environmental and thermal stability in the manufacture of candies and baked goods (English et al. 2023).

Lipid-Based Materials

The alcohol encapsulation has been able to carry out by providing a controlled release of the active ingredient through use of lipid-based carriers (nanoliposomes, solid lipid particles, nano- structured lipids) with over 80% encapsulation efficiency (Fathi et al 2012). Type of lipid and particle size are two factors that can affect the lipid-based carrier form. Carriers based on lipids provide excellent protection against oxidative and evaporative degradation, making it critical to tune these parameters, but high concentrations of alcohol can damage the lipid bilayers.

2.5 Polymer-Based and Hybrid Systems

The majority of the systems investigated for alcohol encapsulation are cellulose derivatives, chitosan, and alginate because of their food-grade status and adjustable physicochemical characteristics. Improved encapsulation efficiency and controlled-release profiles of active ingredients have been observed in chitosan-alginate and protein-polysaccharide hybrid formulations made through ionic/electrostatic interactions (Patil & Paradkar, 2006; English et al., 2023). Hybrid matrices utilise the best qualities of various materials to improve alcoholic content retention and maintain integrity during various food processing operations. Confectioners may benefit greatly from this since it allows their product to maintain its integrity at greater temperatures and release flavour precisely when desired.

Table 1: Evaluation of Different Encapsulation Materials for Food-Based Alcohol Retention

Type of substance	Examples	Alcohol interaction	Consistency in temperature	Applicability to sweets	Advantages	References
Carbohydrates	Maltodextrin, gum arabic, modified starch	Hydrogen bonding and physical entrapment	Moderate	High	Flavourless, inexpensive, and easily dissolved.	Rieneckius (2004); Siccama et al. (2021)
Proteins	Whey protein, gelatin, soy protein	Hydrophobic interactions	Moderate to high	Moderate	Strong capacity to form films	The works of Wang et al. (2018) and English et al. (2023)
Lipids	Phospholipids, triglycerides	Hydrophobic encapsulation	High	Moderate	The volatilisation barrier has been enhanced.	The works of Fathi et al. (2012) and Subramani et al. (2020)
Polysaccharide gels	Alginate, pectin	Ionic crosslinking and matrix entrapment	High	High	Managed release, little volatility	For example, Patil and Paradkar (2006); Guerra-Valle et al. (2022)
Hybrid systems	Protein-carbohydrate blends	Combined electrostatic and physical interactions	High	High	Enhanced stability and efficiency of encapsulation	Rousseau and Charve (2009) and English et al. (2023)

3. Applications in Food Systems

The use of encapsulated alcohol technology has recently increased among food manufacturers to develop a product with improved stability, more control over taste delivery, and an enhanced flavour

experience for the consumer. The alcohol flavour remains consistent when consumers open their baked goods and sweet delights because this method stops the alcohol from evaporating during heating and storage.

Confectionery Products

For sweets like chocolate, gelatin, and sugar confections, the technique of alcohol encapsulation is a game-changer. The method stops alcohol from escaping through the product's exterior or evaporating, and it also ensures that everything is mixed evenly. When encapsulated alcohol is processed into a confection manufactured with chocolate, a substantially greater percentage of the alcohol remains in the finished product than would remain if the alcohol had been included directly into the chocolate product (Shahbazi et al. 2022; Hall et al. 2023 reh); furthermore, the alcohol does not interfere with the melting characteristics or sensory attributes of the chocolate when fully melted. Because the alcohol is not coming into direct contact with the candy's fat component during the encapsulation process, it has less of an effect on the candy's flavour and less chance of fat bloom inside the candy. The encapsulation process keeps the alcohol in chewy candies from breaking down until you eat them.

Bakery Products and Desserts

Because of the extreme heat that bakery products undergo when baked, alcohol encapsulation presents a significant difficulty to these products. Cakes and bread, among other baked goods, can have their alcohol content greatly enhanced by using encapsulation techniques. Spray-dried carbohydrate-protein matrices and lipid-based encapsulation systems have been shown to have retention levels of over 80% after the baking process, compared to a significant loss of free systems (Tolve et al. 2022).

The reason being that the encapsulation method lessens the likelihood of alcohol reacting with the dough components, baked goods with encapsulated alcohol have an improved retention capacity and durability in oxidised circumstances.

Functional and Gel-Based Food Systems

In customised food systems, researchers have examined the regulated release and usefulness of encapsulated alcohol. In addition to traditional sweets. Nano-encapsulation strategies enable the controlled modulation of release rates and improve the stability of the encapsulated material in high-moisture or frozen systems (Fathi et al. 2012). Simultaneous co encapsulation of alcohol with bioactive materials in protein-polysaccharide or lipid-based carriers has been shown to improve the overall stability and uniformity of the matrix properties (English et al. 2023). These cases show how encapsulation technology can be used to include alcohol into different food systems in a variety of ways.

4. Challenges and Limitations

While there is much that is considered innovative regarding the idea used in encapsulation, the use of alcohol in the food process is anything but seamless, and the overall impression is that it is anything but progressive. The hardest component Volatility: It can't stand still for long and will eventually start to flee, particularly in the face of the combined effects of air, heat, and shear forces. This means that no matter how clever you are at hiding your core or how well you insulate You'll end up with an alcoholic disaster since some of the alcohol in your outer layer will still be able to escape.

Gharsallaoui, A., Roudaut, G., Chambin, O., Voilley, A., & Saurel, R. (2007). Applications of spray-d. But then the issue with the materials becomes apparent. Matrixes of carbohydrates are one example. However, an excess of water would be problematic for the composition due to the hygroscopic qualities of carbohydrate matrix, which would lead to the formation of rapid tracks for alcohol.

There is also the fact that the use of encapsulated alcohol systems in food is further constrained by regulatory concerns. When used by a large number of consumers, micro- and nanoscale carriers raise concerns about their food-grade status, safety, and labelling. Another factor that could restrict formulation versatility is regional variations in law and legislation.

Lastly, a standardised evaluation process and publicly available stability outcomes are still missing from the current body of literature. This is due to the fact that the majority of published works don't assess their function or alcohol retention, instead focusing on the efficiency of short-term encapsulation. Making effective encapsulation procedures relies on this.

5. Conclusion

An excellent strategy for adding alcohol to food systems is encapsulation, which eliminates considerable concerns with volatility, temperature instability, and spontaneous release related to the senses. Improvements in nano-scale delivery systems, ionic gelation, complicated coacervation, and spray drying are just a few of the encapsulation technologies that have allowed for more controlled release, stability, and retention.

Core material and physicochemical parameters have a significant impact on how alcohol systems with encapsulation behave. According to Perry and McClements (2020) and English et al. (2023), there are several types of matrices that are utilised for encapsulation, including lipid-based, carbohydrate-based, and hybrid-based matrices. These matrices have different efficiency characteristics and food matrix compatibility.

Despite these advancements, significant concerns regarding regulatory issues, long-term stability, scale-up, and moisture sensitivity remain unresolved. In the future, researchers should aim to standardise evaluation approaches, stabilise processes, and create long-term stability data under actual storage conditions. This information can be used to design better encapsulation solutions for controlled alcohol addition in food.

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