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# 乳清蛋白基微胶囊的制备及应用研究进展

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**摘 要:** 近年来, 微胶囊技术凭借其对活性成分的保护与控释特性, 在食品科学和生物医学领域展现出广阔的应用前景。在多种壁材中, 乳清蛋白因其天然无毒、生物相容性和生物降解性等多种优点而成为颇具潜力的候选者。本文首先概述了乳清蛋白基微胶囊的壳核结构。其次重点探讨了乳清蛋白壁材改性方式: 与其他生物大分子构建复合壁材; 采用物理或化学方法进行结构修饰, 以及利用美拉德反应改善界面特性。再次分析了喷雾干燥法、冷冻干燥法和复合凝聚法的技术特点及其对乳清蛋白基微胶囊性能的影响。研究表明, 通过精确调控工艺参数, 可显著提升微胶囊的包埋率和稳定性。最后在应用领域, 乳清蛋白基微胶囊不仅能够有效保护益生菌活性, 实现活性物质的靶向递送, 还在药物控释系统、创面敷料等生物医药领域展现出应用潜力。
**关键词:** 乳清蛋白; 微胶囊; 制备

## Research progress on the preparation and application of whey protein-based microcapsules

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**ABSTRACT:** In recent years, microcapsule technology has shown broad application prospects in food science and biomedicine due to its protection and controlled release characteristics of active ingredients. Among a variety of wall materials, whey protein has become a promising candidate due to its natural non-toxicity, biocompatibility and biodegradability. This paper first provided an overview of the putamen structure of whey protein-based microcapsules. Secondly, this paper mainly discussed the modification methods of whey protein wall materials: Building composite wall materials with other biological macromolecules; structural modification by physical or chemical methods, as well as improvement of interface properties by Maillard reaction. This paper analyzed the technical characteristics of spray drying, freeze drying and complex coacervation methods and their effects on the properties of whey protein-based microcapsules. The results showed that the embedding rate and stability of microcapsules could be significantly improved by precisely regulating the process parameters. Finally, in the field of

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application, whey protein-based microcapsules could not only effectively protect the activity of probiotics and achieve targeted delivery of active substances, but also showed application potential in biomedical fields such as controlled drug delivery systems and wound dressings.

**KEY WORDS:** whey protein; microcapsules; preparation

## 0 引 言

微胶囊技术是指将固体、液滴或气态的活性物质包裹在惰性壁材中，可用于保护、控释和靶向递送功能性活性物质[1]。伴随微胶囊技术的发展，其制备工艺及新型壁材已被大量开发及优化。作为微胶囊功能化应用的核心要素，壁材的理化性质直接决定了其技术应用边界[2]。在壁材筛选过程中应遵循以下技术准则：首要确保壁材具备良好的稳定性，避免壁材与活性成分之间发生不良反应；同时需优先选择生物相容性材料以符合食品安全标准，还需综合考虑壁材的产业化成本[3]。

蛋白质作为丰富的可再生天然材料，具有生物相容性和生物降解性[4]，已被证实作为微胶囊壁材的可行性[5–6]。其中，乳清蛋白是奶酪生产的副产品，由多种球状蛋白组成，包括 $\alpha$-乳清蛋白(alpha-lactalbumin, $\alpha$-LA)、$\beta$-乳球蛋白(beta-lactoglobulin, $\beta$-LG)、牛血清白蛋白(bovine serum albumin, BSA)、免疫球蛋白以及乳铁蛋白等[7]。乳清蛋白作为包埋材料具有多种功能特性，其中，$\alpha$-LA和$\beta$-LG具有乳化性能，有助于稳定乳液液滴并防止脂质分离，从而防止聚结[8]。$\beta$-LG 具有游离巯基残基和芳香族氨基酸，从而产生抗氧化活性[9]。乳铁蛋白通过螯合铁，抑制有害细菌的生长，具有抗病毒和抗炎活性[10]。基于以上原因，乳清蛋白作为功能性壁材在营养递送系统中的应用日益广泛。影响乳清蛋白壁材功能的重要因素包括粒径大小、分布和表面电荷等物理化学性质[11–13]。目前已有研究报道乳清蛋白的功能特性和基于乳清蛋白的纳米递送系统，许多研究均集中在以乳清蛋白为复合壁材包埋活性物质的可行性上。然而，基于乳清蛋白的微胶囊制备与应用的综述较少。本综述旨在概述乳清蛋白基微胶囊的结构、不同类型的乳清蛋白壁材、乳清蛋白基微胶囊制备过程及其应用，以期为基于乳清蛋白微胶囊的设计、生产和应用提供新的见解。

## 1 乳清蛋白基微胶囊结构

微胶囊通常被定义为尺寸在 1~1000 μm 的具有壳核结构的颗粒[14]。根据芯材数量分为单核心微胶囊和多核心微胶囊，同样，根据壁材层数分为单层微胶囊和多层微胶囊[15–16]。微胶囊的结构赋予了微胶囊不同的性质和应用途径。单核微胶囊具有较大的核心体积和较高的包封率，是一种潜在的递送载体，但一旦外壳破裂，内容物就会迅速释放。多层微胶囊在夹层中负载不同的活性物可以实现逐步释放，在夹层中负载相同的活性物可以实现持续释放，使其成为控制药物释放、风味释放和食品保存应用的理想选择[17]。有研究表明以乳清蛋白和果胶为壁材料封装该鼠李糖乳杆菌 ZFM231 菌株，采用乳化凝胶技术，制备双层微胶囊，其包封率达到 89.46%；该菌株在胃液中仅损失 1.96 U，微胶囊到达肠液后释放率达到 86.56%，实现微胶囊缓控释放[18]。

## 2 乳清蛋白壁材类型

乳清蛋白基微胶囊根据其壁材组成可分为 3 类：单乳清蛋白基微胶囊，其利用乳清蛋白作为唯一壁材[19]；复合乳清蛋白基微胶囊，其利用乳清蛋白和其他组分组合以增强壁材性能[20]；修饰的乳清蛋白基微胶囊，乳清蛋白可以通过物理、化学和生物方法进行修饰，通过改变蛋白质的线性表位或空间构象实现特定特征[21]。

### 2.1 单乳清蛋白基壁材

天然状态的乳清蛋白由致密的球状蛋白组成，主要成分是 $\beta$-LG 和 $\alpha$-LA。$\beta$-LG 约占乳清蛋白总量的 50%，具有完善的一级、二级、三级和四级结构；$\alpha$-LA 约占总乳清蛋白的 20%，大多结构相对无序，但热稳定性较好[22]。乳清蛋白本身是高营养的食品成分，是必需氨基酸的良好来源[23]。此外，通过调节 pH、离子强度和温度等环境条件，可改变乳清蛋白的表面性质，进而调控其分子相互作用[24]。DUONGTHINGOC 等[25]调整乳清蛋白溶液 pH 至等电点，利用凝聚现象，通过喷雾干燥法制成壁材包裹酵母菌。结果表明在合适的温度及酸性pH条件下乳清蛋白快速聚集形成壁材，该微胶囊利于提升酵母菌的成活率。KHEM 等[26]以乳清蛋白为壁材，通过喷雾干燥包埋两种植物乳杆菌菌株 A17 和 B21，结果表明该微胶囊在 20 ℃下的储存试验期间保持活力至少 8 周。然而，单乳清蛋白基微胶囊在制备和应用过程中均受到环境条件限制。因此，通常选择复合乳清蛋白壁材或修饰的乳清蛋白壁材用于定制微胶囊，使其在包埋中展现优异的保护性能。

### 2.2 复合乳清蛋白基壁材

#### 2.2.1 乳清蛋白和多糖

淀粉、纤维素、壳聚糖、葡聚糖和海藻酸钠等属于可再生的多糖，可通过共吸附、物理或共价键合以及逐层沉积等方法与乳清蛋白形成复合物，可改善乳液 pH 稳定性，

并提高包埋率。ZHAO 等[27]以柠檬酸酯化马铃薯淀粉和乳清蛋白为乳化剂制备水包油叶黄素乳液，并通过喷雾干燥技术构建微胶囊。柠檬酸盐酯化马铃薯淀粉具有良好的乳化性能，与乳清蛋白复配时，微胶囊的包埋效率增加，且高比例的乳清蛋白有助于改善微胶囊的包埋率和热性能。LI 等[28]以低聚果糖和乳清蛋白为复合壁材，包埋黑大豆皮花青素。结果表明，与游离花青素和矢车菊素-3-葡萄糖苷相比，该微胶囊表现出优异的抗氧化能力，在胃期和肠道期都表现出增强的花青素保留能力。复合壁材也可以用来制备多层微胶囊。JIN 等[29]以羟丙基-$\beta$-环糊精为内壁，乳清蛋白为外壁，采取复合壁材逐层组装方法，将腺苷封装在核心材料内，旨在通过分子间相互作用增强腺苷微胶囊的稳定性。结果表明，该微胶囊包埋率为 36.80%，释放行为测试下 24 h 保留率为 76.09%，这种微胶囊在具有缓释特性的储存和递送系统中显示出广阔的应用前景。乳清蛋白通过与多糖的非共价和共价相互作用充当微胶囊壁材，有效改善了单乳清蛋白基微胶囊的热不稳定性和 pH 敏感性。

2.2.2　乳清蛋白和其他蛋白质

乳清蛋白可以与明胶、大米蛋白和酪蛋白结合形成微胶囊的复合壁材[30–32]。FUSTIER 等[33]以乳清蛋白分离物和鱼明胶为壁材，以亚麻籽油为芯材，通过改变复合壁材的浓度配比来探究微胶囊的理化性质。结果表明，0.5%乳清蛋白和 0.75%鱼明胶制成的多层乳液在 21 d 后表现出最低的氧化性，是由于鱼明胶的电荷效应可能会阻止金属离子与亚麻籽油相互作用。HU 等[34]以 80%酪蛋白和 20%乳清蛋白作为壁材包埋藻油和金枪鱼油，结果表明，藻油和金枪鱼油微胶囊在模拟胃期后释放率线性增加至 77.7%和 41.7%，两种微胶囊的释放率和蛋白质水解之间呈显著正相关。但涉及乳清蛋白的双蛋白壁材微囊技术应用较少，可能是由于乳清蛋白的界面活性和球状形态，导致在微胶囊包埋中产生分子间空隙，成品微胶囊包埋率较低[35]。ZHUNG 等[36]使用乳清蛋白和酪蛋白酸钠的复合物制备共轭亚油酸微胶囊。结果表明这些微胶囊具有较低的包埋率和氧化稳定性，这可能是因为酪蛋白这种超分子聚集体与胶体磷酸钙形成胶束，影响微胶囊芯材的稳定性。

### 2.3　修饰的乳清蛋白壁材

2.3.1　物理修饰

乳清蛋白中 $\beta$-LG 和 $\alpha$-LA 均是具有二硫键的球状蛋白，$\beta$-LG 由于含有活性巯基会自聚集，最终形成凝胶网络[37]。虽然 $\alpha$-LA 无法引发聚集反应，但一旦 $\beta$-LG 开始自聚集，它可能会参与凝胶化过程。各种物理修饰技术，包括加热、超高压、超声和微波，已被用于诱导蛋白聚集和改变高级结构。DUONGTHINGOC 等[25]以乳清蛋白为壁材，发现乳清蛋白在 70~90 ℃喷雾干燥后部分变性，这说明温度状态和机械剪切在一定程度上使蛋白质分子的球状构象不稳定。尽管物理改性方法有安全性、无毒和成本效益等优点，但它们通常比其他方法需要更多的关注环境条件。

2.3.2　交　联

蛋白质与多酚类化合物结合形成的复合物，既可以修饰蛋白质，也可以保证多酚活性。多酚的引入可以改善乳清蛋白界面特性和功能特性，增强壁材的稳定性[38]。FAN 等[39]通过自由基接枝制备了乳清蛋白与没食子儿茶素-3-没食子酸酯偶联物，并将其用作乳化剂来稳定鲱鱼油。结果表明，该偶联物表现出比乳清蛋白更强的抗氧化能力。FEI 等[40]发现，乳清蛋白通过共价键与没食子酸-原儿茶酸交联后，乳化稳定性指数提高了 14.9 min。此外，乳清蛋白与没食子酸-原儿茶酸的结合使复合壁材变性温度提高了 17.92 ℃，表明该共价复合物的热稳定性有所提高。ROJAS-MORENO 等[41]使用鞣酸、三聚磷酸钠、氧化鞣酸和转谷氨酰胺酶作为交联剂，对乳清蛋白复合壁材进行改性，用来包埋橙花精油。结果表明多酚交联壁材展现出最高的包埋率，与没有交联的壁材相比提高了 400%。但多酚和乳清蛋白之间主要依赖于非共价相互作用，这一特性导致交联微胶囊具有高 pH 和离子强度敏感性，从而限制了多酚在乳清蛋白基微胶囊中的更广泛应用。

2.3.3　美拉德反应

美拉德反应是一种基本的蛋白质修饰方法，将蛋白质与多糖共价接枝以产生稳定的复合物，从而显著增强蛋白质的物理化学性质，如乳化性质、热稳定性和凝胶强度[42]。这些美拉德反应产物表现出很强的抗氧化活性、良好的乳化性能和成膜性能，可用于制造微胶囊的抗氧化壁材[43]。LIAO 等[44]采用湿热法制备乳清蛋白和低聚木糖的美拉德反应产物，通过喷雾干燥包埋鼠李糖乳杆菌，证实该壁材提高了微胶囊在体外消化过程中的稳定性。AMINIKHAH 等[45]将乳清蛋白、大豆分离蛋白和明胶与麦芽糖糊精通过美拉德反应偶联，然后用于封装 *Satureja khuzestanica* 精油，证实乳清蛋白-麦芽糖糊精复合壁材包埋效率最高为 89.27%，且基于美拉德反应的微胶囊壁材比蛋白质-多糖壁材具有更高的抗氧化活性。WANG 等[46]以乳清蛋白和麦芽糖制备美拉德反应产物，改性的乳清蛋白表现出更好的乳化、发泡和抗氧化性能。利用乳清蛋白-麦芽糖和阿拉伯胶络合物凝聚，制备包埋率为 87.41%金枪鱼油微胶囊。乳清蛋白-麦芽糖作为壁材形成的微胶囊增强了金枪鱼油的氧化稳定性。

## 3　乳清蛋白基微胶囊的制备方法

乳清蛋白是一种天然乳化剂，因为它具有两亲性结构、高营养价值和良好的成膜性，可通过膜乳化或络合凝聚制备微胶囊的优良壁材[47]。乳清蛋白基壁材最常用的微胶囊制备技术是喷雾干燥和冷冻干燥[48–49]。喷雾干燥法具有灵活性高、适用性广、成本低和可连续操作的优点，其包埋效率一定程度上依赖壁材溶液的乳化性[50]。冷冻干燥

技术能在极低温度的真空条件下进行干燥，可以减少热损伤，保护敏感的生物活性物质。该方法可最大限度地减少对蛋白质的不可逆损伤，例如聚集和变性[51]。

### 3.1 喷雾干燥法

喷雾干燥法通常分为两个步骤：首先将壁材和芯材溶解或分散在水中，制备初级乳液或悬浮液；其次将乳液或悬浮液雾化并喷雾干燥，形成最终的微胶囊化产物，该工艺可以根据进料溶液的特性和操作条件生产不同粒度的粉末[52]。喷雾干燥因其操作简单、低成本和高效率在微胶囊生产中获得了广泛的普及。但是该技术很容易受乳液性质、设备类型和工艺条件等影响，从而影响微胶囊的形态、粒径、包埋率、吸湿性和溶解度等[53–55]。CALVA-ESTRADA 等[55]通过喷雾干燥对可可液和乳清蛋白的纳米乳进行微胶囊化，证实在较高的入口干燥温度下，生物活性化合物的微胶囊收率和挥发性化合物的保留率更高。ZHANG 等[56]将乳清蛋白和柠檬酸盐绿豆淀粉按不同比例制备壁材，微囊化辣椒素，结果表明包埋体系中乳清蛋白含量高的微胶囊包埋效率和产量更高，颗粒表面更光滑。庄丰辰等[57]分别用乳清蛋白和牛乳浓缩蛋白作为壁材，以极易氧化的多不饱和脂肪酸为芯材，通过喷雾干燥的方式制备微胶囊，结果表明以乳清蛋白为壁材，在芯壁比为 1:8 下微胶囊包埋率较高，芯材的氧化稳定性较强。而牛乳浓缩蛋白作为壁材，其微胶囊包埋效率较低，表面孔洞多，且芯材氧化速度较快。因此，选择适当的芯壁材、优化芯壁材比例、提升乳化技术以及调整工艺参数对于提升乳清蛋白基微胶囊的质量和功能至关重要。

### 3.2 冷冻干燥法

冷冻干燥是一种通过升华冷冻样品制备不规则和高度多孔微胶囊的技术。因为该技术在低温下进行，所以利于保存热敏活性物和益生菌活力[58–59]。LEDRI 等[60]以麦芽糖糊精和乳清蛋白为壁材，以冷冻干燥和喷雾干燥两种封装方法制备叶绿素微胶囊，结果证实冷冻干燥比喷雾干燥更有效地保护叶绿素。CHAABANE 等[61]以麦芽糖糊精和乳清蛋白为壁材，通过喷雾干燥和冷冻干燥制备橄榄油微胶囊，结果表明，经喷雾干燥处理的微胶囊呈现球状凹痕结构，经冷冻干燥处理的微胶囊呈扁平片状，表面不规则。ERATTE 等[62]以乳清蛋白和阿拉伯胶为壁材，通过喷雾干燥和冷冻干燥制备金枪鱼油微胶囊，结果表明，与冻干微胶囊相比，喷雾干燥的微胶囊具有更好的抗氧化稳定性、更高的包埋效率。喷雾干燥的微胶囊表面没有出现微孔，而冻干的微胶囊表面多孔。冷冻干燥技术的冷冻速率和温度会影响冰晶形成，从而影响微胶囊的外观及功能[63]。且该项技术能量消耗、冻干成本及干燥时间都较高，这些因素会限制冻干微胶囊的应用。

### 3.3 复合凝聚法

复合凝聚法制备微胶囊的原理是在特定条件下，通过静电相互作用吸引两种具有不同电荷的大分子物质相互结合，形成复合凝聚材料，从而包埋疏水性芯材[64]。该方法适用于乳清蛋白与多糖的复合壁材，因为多糖在较宽的 pH 范围内带负电荷，而蛋白质在等电点以下带正电荷，二者通过静电作用相互吸引[65]。通过复凝聚法制备微胶囊的过程不涉及加热处理，可以最大程度地保护芯材。HUANG 等[66]将乳清蛋白-亚麻籽胶和甘油单二酯脂肪酸复合凝聚成壁材，用于白藜芦醇微囊化，该微胶囊表现出不规则的薄片或块状褶皱的外观，包埋率达到 96%，白藜芦醇的抗氧化能力通过与复合壁材络合也得到提高。但反应介质的 pH、聚合物浓度、聚合物分子量等多个因素均影响复合聚结物的形成和微胶囊的性质[67–68]。MICHEL 等[69]以乳清蛋白和果胶为壁材，采用复凝聚法微胶囊化印楝叶提取物，结果表明在凝聚中影响最大的因素是 pH。

## 4 乳清蛋白基微胶囊的应用

乳清蛋白基微胶囊的应用可分为食品科学和生物医药两方面。乳清蛋白具有高营养价值，被广泛用于食品配方。因为乳清蛋白具有良好的凝胶性能，乳清蛋白基微胶囊在食品科学应用中具有应用价值，如益生菌保护、食品强化等。另外，乳清蛋白有良好的抗炎[70]和抑菌作用[71]，在生物医学方面，如药物递送和伤口敷料等具有很大的开发潜力。

### 4.1 食品科学

#### 4.1.1 益生菌保护

益生菌是人类有益的共生微生物，对其功能性食品的需求逐渐增加。益生菌必须在食品生产、加工和储存过程中保持其活力[72]。微胶囊化技术有利于提升益生菌类在食品和胃肠道中的存活率，且用于益生菌微胶囊化的材料应为食品级且安全无毒[73]。KHORSHIDI 等[74]以乳清蛋白和黄原胶基为壁材对嗜酸乳杆菌微囊化，结果表明与游离菌相比，微囊化嗜酸乳杆菌在酸奶中的活力增加，在储存期间为 2.16 log CFU/g，在模拟胃肠道条件下为 3.52 log CFU/g。HAN 等[75]将保加利亚乳杆菌微囊化，制备双层壁材：内层由转谷氨酰胺酶诱导的乳清蛋白分离物凝胶形成，外层采用海藻酸钠交联钙离子凝胶法形成。结果表明该微胶囊中益生菌的存活率从 3%提高到 41.26%。ÇABUK 等[76]以乳清蛋白-支链淀粉为壁材微囊化嗜酸乳杆菌 NRRL-B4495，结果表明在模拟胃液中，微囊化 NRRL-B4495 计数仅下降 1.17 log CFU/g；在胆汁盐溶液中孵育中，微囊化 NRRL-B4495 计数仅下降 1.35 log CFU/g，说明该微胶囊提升 NRRL-B4495 在胃液和胆汁中的稳定性。CHEN 等[18]采用乳化-凝胶技术，以乳清

蛋白和果胶为壁材料封装鼠李糖乳杆菌 ZFM231 菌株，制备双层微胶囊。结果表明，在 4 ℃下储存 28 d 后，ZFM231 计数仅下降 1.57 log CFU/g，在 25 ℃下储存 14 d，计数下降 1.79 log CFU/g，说明双层微胶囊可以显著提高细菌的储存能力。

4.1.2　食品强化

乳清蛋白基微胶囊在食品工业生产中有许多优点，它可以封装抗菌、抗氧化和抗褐变物质，可开发生产保质期更长的功能性产品。KIM 等[77]以交联豌豆淀粉-乳清蛋白混合物-麦芽糖糊精复合物为壁材，微囊化 $\beta$-胡萝卜素，结果表明由于交联豌豆淀粉和麦芽糖糊精添加导致蛋白质的两亲性 $\beta$ 片结构增加，提高 $\beta$-胡萝卜素微胶囊的稳定性，该微胶囊能应用于蛋黄酱高脂肪产品。CRUZ-MOLINA 等[78]使用乳清蛋白和果胶通过纳米喷雾干燥封装葡萄渣多酚，包埋后的多酚抗氧化能力高于游离多酚，且 82%顺利通过胃肠道消化，该微胶囊具有用作营养保健品的潜力，具有高抗氧化能力。MOUSA 等[79]用乳清蛋白和海藻酸钠对双歧杆菌 F-35 进行微胶囊化，加入该微胶囊的酸奶黏度和弹性提升，可以改善凝固酸奶的流变特性。

### 4.2　生物医药

鉴定乳清蛋白水解物中具有生物活性的多肽序列，研究这些多肽组分的自组装、凝胶形成和乳剂稳定能力，对合理设计生物活性载体具有重要意义。乳清蛋白水解物已成功制成微粒用于包封水溶性营养物质[80]。MEZERJI 等[81]以改性淀粉、麦芽糖糊精和乳清蛋白浓缩物为壁材微囊化何首乌多酚，将其补充给受肠致病性大肠杆菌攻击的小鼠，小鼠的体重增加，减轻肝酶的产生和脂质过氧化，表明该微胶囊可对抗小鼠大肠杆菌感染。ZHANG 等[82]以海藻酸盐和乳清蛋白为壁材微囊化香芹酚，观察在猪胃肠道中的释放动力学。结果表明，微囊化技术有效减少了香芹酚在猪胃中的吸收，在喂食后 5 h，34.1%的香芹酚仍残留在空肠中。回肠中的回收率仅为 3.5%，表明大部分香芹酚从微胶囊中释放出来，并在通过空肠的转变过程中被明显吸收或代谢。AHAD 等[83]以乳清蛋白和阿拉伯树胶为壁材微囊化生姜油树脂，结果表明，对比阿拉伯树胶基微胶囊，乳清蛋白基微胶囊包埋量高达 89.57，对大肠杆菌的抑制直径为 16.64 mm，对金黄色葡萄球菌的抑制直径为 22.68 mm，乳清蛋白基微胶囊表现出更高的抑菌活性。总体来说，虽然乳清蛋白与多糖类壁材组合更多地被选择用于食品应用方面，但鉴于其低毒性、抗菌性、胃蛋白酶抵抗性、生物相容性和生物降解性，乳清蛋白作为良好壁材在药物递送、药物释放和伤口敷料等生物医药方面也有显著潜力。

## 5　结束语

本文综述了利用乳清蛋白为壁材的微胶囊化技术。(1)乳清蛋白基微胶囊是壳核结构；(2)乳清蛋白作为单独壁材使用，可能会受到环境因素的影响，通常将其与多糖类物质混合或改性以获取优良壁材，未来可以重点开发乳清蛋白与其他材料的复合壁材，扩大其应用范围；(3)乳清蛋白基微胶囊的制备方法，需以芯壁材的理化性质为首要考虑因素，壁材类型、壁芯比和 pH 等因素也会影响其性质；(4)乳清蛋白基微胶囊的应用领域集中于食品科学，尤其在益生菌保护方面。未来仍需要探索和开发乳清蛋白基微胶囊在生物医药方面的应用，推动乳清蛋白基微胶囊多功能化发展，以满足不同领域的一系列需求和挑战，从而增加其价值和市场竞争力。

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