# 中药衍生孢粉素微胶囊: 载药机制、递药应用及其挑战

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**摘要**: 孢粉作为经典的中草药之一, 具有悠久的药用价值, 不仅在疗效方面表现出色, 且通过脱脂与去除内容物能够构建孢粉素空腔结构, 可作为高效的药物载体。相较于合成载体, 孢粉素作为天然生物材料, 凭借其优异的生物相容性、理化稳定性和尺寸均一性, 在生物医学领域展现出多重应用价值, 已成功实现对抗肿瘤药物、蛋白质等活性成分的高效负载, 且通过表面修饰技术还可进一步开发智能给药系统。本文对中药来源孢粉素的制备工艺、载药机制、给药系统设计原理及其在靶向递送和响应性释放等智能给药系统的研究进展进行总结, 探讨其发展前景, 以期为推动中药衍生孢粉素微胶囊在生物医药领域的广泛应用提供理论参考与技术支撑。

**关键词**: 孢粉素; 孢粉分类; 孢粉素的提取方法; 孢粉素载药方法; 载药应用

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# Traditional Chinese medicine-derived sporopollenin microcapsules: drug-carrying mechanism, drug delivery applications and their challenges

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**Abstract**: As one of the classic Chinese herbs, spore powder has a long history of medicinal value, not only in terms of therapeutic efficacy, but also through the defatting and removal of the contents can be constructed sporopollenin (SP) cavity structure, which can be used as a highly efficient drug carrier. Compared with synthetic carriers, sporopollenin, as a natural biomaterial, has demonstrated multiple applications in biomedical fields by virtue of its excellent biocompatibility, physicochemical stability, and dimensional homogeneity, and has successfully achieved efficient loading of anti-tumour drugs, proteins, and other active ingredients, and can be further developed into a smart drug delivery system by surface modification technology. In this paper, we summarise the preparation process, loading mechanism, drug delivery system design principle of sporopollenin from traditional Chinese medicine, and its research progress on intelligent drug delivery system, such as targeted delivery and responsive release, and discuss its development prospect, with a view to providing theoretical references and technological support for the promotion of the wide application of traditional Chinese medicine-derived sporopollenin microcapsules in the field of biomedicine.

**Key words**: sporopollenin; classification of spore powder; the extraction method of sporopollenin; the drug loading method of sporopollenin; drug loading application

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在中药材的广泛应用中, 不同部位因其独特的药用成分与药理作用而被挑选入药, 主要包括根部、茎干、叶片、花朵、果实、种子、孢粉等。其中, 孢粉类药材是极具代表性的传统中药之一。从先秦时期的《神农本草经》开始, 就有关于孢粉入药的记载, 此后历代医书如《金匮要略》、《唐本草》、《本草纲目》等均有详细记述。在现代研究中, 中药孢粉不仅在疗效方面表现出色[1], 因其独特的物理结构和化学特性, 通过化学或化学加酶等方法处理即得空心壳结构的中药衍生孢粉素, 使其能够作为理想的微型容器[2-4]。

孢粉素的多孔结构、高比表面积、高附着力以及优异的生物相容性[5], 为药物的负载、释放和靶向输送提供了有利条件[6]。此外, 孢粉素富含多羟基化脂肪族成分与聚酮衍生脂肪族 $\alpha$-吡喃酮元素[7-9], 其核心结构是由羟基脂肪酸交联的聚合物苯丙烷衍生物[10], 表面具有足够丰富的基团, 亦容易通过表面修饰构建功能化递药载体, 精准递送药物至特定组织或细胞[11,12]。孢粉素与其他基质材料复合后, 能够有效调控基质的亲水特性, 同时增强其抗菌与抗氧化性能。与传统包合技术相比, 孢粉素载药系统具有天然性, 在载药效率、释放可控性及生物相容性等方面表现更为优异, 尤其适用于复杂胃肠道环境下的药物递送, 并能提升难溶性药物的生物利用度。此外, 孢粉素不仅可负载小分子药物, 还能有效包封蛋白质、核酸等大分子药物, 例如利用其孢粉素外层抵抗酶解作用, 确保药物稳定性。相比之下, 环糊精等包合技术受限于分子尺寸, 难以高效负载活菌制剂或基因治疗载体等复杂结构的药物形式。

本文旨在综述用于载药系统的中药孢粉, 从结构分类、提取技术到载药方法及应用实例进行详尽总结, 为后续研究中药孢粉素的制备和载药提供参考。其中孢粉素的提取未有普适性且绿色的方法, 且提取出来后的孢粉素也缺少一套系统的评价方法。

## 1 孢粉的种类

根据孢粉学分类标准, 孢粉特指为花粉和孢子, 两者在结构特征上存在异同点。花粉可依据以下形态学特征进行系统划分: 首先按其聚合状态可分为单粒花粉和复合花粉 (如多聚体、四分体等); 其次依据几何形态特征可区分为囊状、多边形、异形及弧形等类型; 再者根据萌发孔特征分为单萌发孔型、三萌发孔 (三沟) 等。此外, 外壁纹饰的显微结构特征 (如网状纹饰、刺状纹饰等) 也是重要的分类依据, 表 1 所列扫描电子显微镜图像均引自《Illustrated Pollen Terminology》[13]。孢子也可根据形态 (如球形、四面体等)、表面纹饰 (如网状、瘤状等) 进行分类。不同点在于花粉根据萌发孔进行分类, 而孢子根据射线 (裂缝) 进行分类, 可分为单射线和三射线。

研究证实, 孢粉的种类与结构特征是影响载药效率的关键因素之一。不同表面特性的孢粉素适用于不同的载药方式, 如白蜡树孢粉素因大孔网状结构限制离心法对牛血清白蛋白的装载效率; 松树孢粉素的窄孔疣状表面则导致被动/离心载药困难; 而椴树孢粉素凭借穿孔表面结构在离心载药中表现出最优包封效率。因此对于具有相似外壁结构的孢粉素, 可建立工艺参数传递模型: 以石松孢子为例, 对与石松孢子具有相似结构的 Polemoniaceae (*Phlox paniculata*) (图 1A[13]) 孢粉来说, 其孢粉素提取及载药工艺或可相互借鉴。针对具有裂缝的孢粉 (如石松孢子), 可借鉴载药方法为通过与二氧化硅纳米颗粒复合压片实现沟槽孔隙扩张, 在负载益生菌等活性物质后, 利用表面活性剂介导的界面张力效应实现孔隙重构, 实验数据证实该工艺能有效维持生物活性[14]。双气囊结构孢粉 (如松科) 采用分区载药策略: 通过差异化加载方式分别将药物导入气囊腔室与中央核区, 在体内释放可以达到协同作用[15]。该技术可拓展至三气囊结构的 Podocarpaceae (*Pherosphaera hookeriana*) (图 1B[13]), 其多腔室结构为协同载药与释放提供新思路。

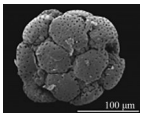
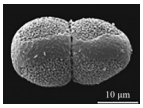
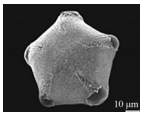
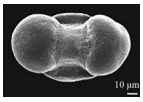
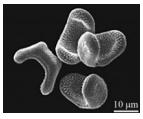
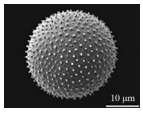
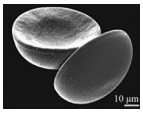
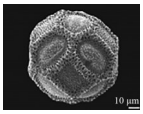
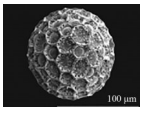
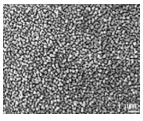
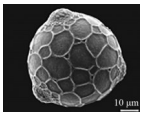
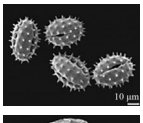
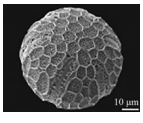
然而, 虽传统医学文献对孢粉的药用价值已有详尽记载, 但当前用于药物递送的孢粉种类相对有限, 常见包括豚草、洋甘菊、玉米、松树及油菜花等来源的孢粉。这种选择性可能与其微观结构特性密切相关: 例如, 壁薄的孢粉在提取过程中易发生结构变形 (图 1C[16]), 增加工艺难度; 而表面具尖刺结构的孢粉[17]能延长胃肠道滞留时间 (图 1D[18]), 并表现出光热转化效应。目前, 不同形态孢粉的释药特性差异尚未系统研究, 且因其表面结构各异, 载药机制也存在显著区别, 但现有研究孢粉载体多为其去除蛋白质等内容物的孢粉素。

## 2 孢粉素的定义及性质

孢粉素作为一种惰性的天然聚合物, 构建孢粉的外壁, 保护精子细胞, 因其具有尺寸均匀性、多孔性、两亲性、附着力、化学稳定性、抗紫外线、生物相容性及可修饰表面特性等优势, 能在孢粉内核空腔化处理后, 成为优良的药物载体。

孢粉素具备良好的单分散性和尺寸均匀性, 且其微米级空腔结构[19]可有效封装大分子药物及微生物活性细胞等。因孢粉素具有天然的表面孔道 (表 1 中 aperture[13]), 进行脱脂和酸解等操作后, 表面还会形成更多的纳米孔道, 为药物的进入提供最大的便利。孢粉素具有优良的化学稳定性, 使其在强酸、强碱及高温条件下仍然能维持结构稳定性, 且大多数生物酶如蛋白酶、淀粉酶、果胶酶及纤维素酶都不能降解孢粉素,

**Table 1** Pollen classification according to palynology

| Classify | Kind | Scanning electron microscopy | Name |
|---|---|---|---|
| Units | Monad |  | *Lamium galeobdolon* |
| | Polyad |  | *Cymbopetalum aequale* |
| | Dyad |  | *Zeylanidium olivaceum* |
| Shape and polarity | Saccus, bisaccate |  | *Abies cephalonica* |
| | Outline polygonal |  | *Viola arvensis* |
| | Heteropolar |  | *Limnanthes douglasii* |
| | Cup-shaped |  | *Heliconia sp.* |
| Aperture | Inaperturate |  | *Phoebe sheareri* |
| | Colpus/colpate, stephanocolpate |  | *Galium lucidum* |
| | Pantoaperturate, pantocolpate |  | *Opuntia basilaris* |
| | Porus/porate, pantoporate |  | *Cobaea scandens* |
| Ornamentation | Granulum/ granulate |  | *Clarkia purpurea* |
| | Reticulum/ reticulate |  | *Vigna speciosa* |
| | Echinus/echinate |  | *Petasites albus* |
| | Bireticulate |  | *Ocimum basilicum* |

其化学惰性源于其独特的交联结构, 即苯丙烷类衍生物 (愈创木基木质素单元G等)。历经4.5亿年地质变化的孢粉素化石仍能保持结构的完整性[20,21], 为其超长稳定性提供了直接证据。但通过酸碱处理实现孢粉素表面极性重组, 其润湿性的改变为亲脂/亲水性药物提供了差异化载药路径[22]。体外实验证实孢粉素同样具有良好的生物安全性[23,24], 且能在人血浆中部分降解[25], 避免了长期滞留风险, 进一步证明了孢粉素作为药物载体的安全性。

## 3 孢粉素的提取

成熟孢粉颗粒主要由孢粉壁 (含外壁和内壁) 和内部细胞质构成。其中, 内壁作为孢粉壁的最内层结构, 其主要成分为纤维素和果胶, 对酸碱环境较为敏感。外壁结构致密, 由抗性较强的孢粉素、纤维素和角质等物质组成, 可进一步细分为两个亚层结构: 外壁内层和外壁外层。

对于外壁结构来说, 有些水生植物的花粉, 只有一层壁 (如大叶藻属)。在孢子上, 外壁之外一般又有一层薄而透明的壁, 称为周壁。与外壁外层结合较为松散, 在酸碱处理时容易发生剥离。外壁内层结构相对简单, 缺乏表面雕纹, 可依据其密度差异分为内内层和内外层。最具特征性的外壁外层 (即雕纹层) 呈现多样的表面纹饰, 其超微结构又可区分为: 外部的覆盖层 (外外层) 和内部的柱状层 (外内层)。

孢粉经处理后, 其表面的不饱和磷脂和内部过敏原等物质被去除, 形成具有空腔结构的孢粉素, 可作为药物载体或疫苗递送系统。孢粉素的制备通常包括两个步骤: 脱脂和内容物去除 (图2A[3])。内容物去除主要有3种方法: 化学提取法[26-28]、化学−酶联法[2,29]和离子液体法[30]。这些方法均通过清除孢粉表面磷脂和内部物质来获得载药空腔。此外, 近期研究[31]提出了一种新策略, 即通过物理压片使孢粉沿天然沟壑裂开, 无需额外造孔或去除成分, 即可直接负载药物。

孢粉素制备完成后, 可从3个方面进行表征: 蛋白质含量分析、表面形态评价及热稳定性评估。蛋白质含量可通过CHN元素分析、十二烷基硫酸钠-聚丙烯酰胺凝胶电泳、傅里叶变换红外光谱及共聚焦扫描电镜等方法测定。表面形态特征 (大小、分布、形状、直径、纵横比、圆度等) 可通过扫描电镜、透射电镜及动态图像颗粒分析进行定量评价。此外, 热重分析可揭示孢粉素中不同成分的热稳定性。该表征体系可全面评估孢粉素的理化性质, 为其在药物递送等领域的应用提供依据。

### 3.1 脱脂

在孢粉素制备过程中, 脱脂是关键步骤之一。目

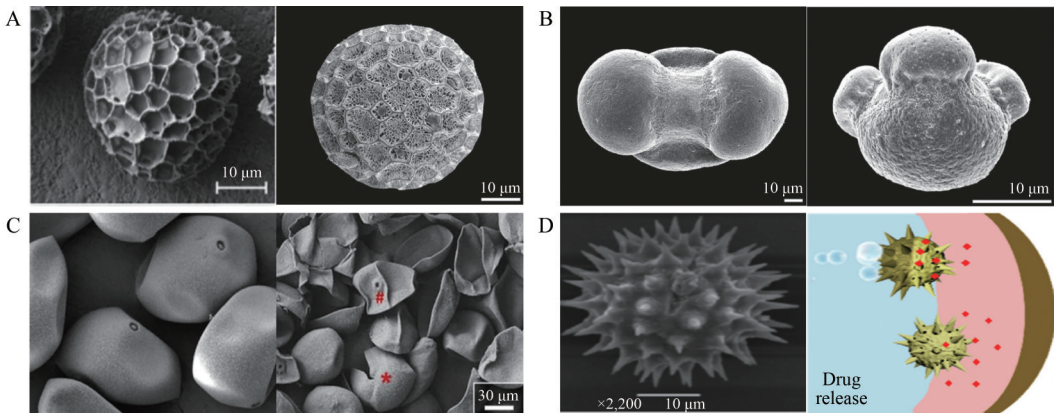



**Figure 1** Structural similarity analysis diagram of sporopollenin and structure-extraction-application relationship diagram. A: Scanning electron microscopy (SEM) image of Lycopodium spores. Adapted from Ref. 13 with permission, copyright 2018 Springer Cham; B: SEM image of pollen in the shape of sacs. Adapted from Ref. 13 with permission, copyright 2018 Springer Cham; C: Unprocessed *Zea mays* pollen and severe rupturing (*) and buckling (#) after processing. Adapted from Ref. 16 with permission, copyright 2016 Scientific Reports; D: SEM image of sunflowers. Adapted from Ref.18 with permission, copyright 2024 Bioactive Materials

前主要采用有机溶剂法, 其中丙酮因其高极性特性成为最常用的脱脂溶剂, 可有效溶解孢粉表面的不饱和磷脂[26,28]。部分研究采用石油醚 (低极性溶剂) 进行脱脂[32,33]。此外, 也有研究采用复合溶剂体系, 如先用水去除亲水性成分, 再结合丙酮/环己烷[34]或丙酮/乙醚[35]进行脱脂。虽然丙酮和石油醚都是常规脱脂溶剂, 但针对不同来源的孢粉, 其最佳脱脂溶剂选择尚缺乏系统性研究。

### 3.2 孢粉内容物的去除

为获得中空的孢粉素结构, 脱脂后的孢粉需进一步去除内部内容物。这些内容物主要包括营养组分 (如蛋白质、脂类、维生素及矿物质)、多种酶类及生物活性物质 (如黄酮类化合物)。目前常用的内容物去除方法主要分为3类: 化学提取法 (图2B[36])、化学–酶解联用法 (图2C) 及离子液体处理法 (图2D[37])。

**3.2.1 化学提取法** 化学提取法主要通过酸碱处理实现内容物去除。具体操作包括: 将脱脂孢粉悬浮于磷酸溶液处理, 经水及有机溶剂多次洗涤后干燥; 或先采用氢氧化钾回流提取, 再经磷酸处理[38]。其中, 磷酸能有效清除内层残留肽及多糖, 而氢氧化钾则可去除大部分蛋白质并将酯类水解为羧酸盐。该方法的主要优势在于工艺成熟、适合规模化生产, 但存在环境污染风险较高、后续纯化步骤繁琐等局限性。

酸碱提取法在孢粉素制备中的应用存在显著的物种差异性。以石松孢子为例, 可采用3种处理方案: 先碱解后酸解[28], 酸解后配合溶剂大量洗涤[39], 先酸解后碱裂解[40]。然而, 这种先碱后酸的方案并不具有普适性, 如豚草孢粉采用该顺序处理会导致结构严重破损[41]。但扫描电镜观察到的“结构破损”可能源于碱处理过程中外溢内容物在孢壁表面的残留附着, 而非真正的结构破坏。因此, 调整酸碱处理顺序可有效改善这一现象。

**3.2.2 化学–酶解联用法** 酶辅助提取法通过生物酶特异性水解孢粉内容物, 常用的酶制剂包括蛋白酶、淀粉酶、果胶酶及纤维素酶等[42]。以松花粉提取为例, 先经50%乙醇变性, 热乙醇–二恶烷脱脂, 稀硫酸/亚硫酸钠预处理, 最后采用牛胰酶消化, 以悬浮液形式储存在50%乙醇中[29]。该方法优势在于环境友好性, 显著降低有毒试剂用量; 但存在酶制剂成本较高的问题, 较传统化学法经济性稍逊, 且少有实验对其进行外观或元素表征。

**3.2.3 离子液体处理法** 离子液体作为一种在100 ℃以下仍保持液态的特殊熔融盐, 其结构特征表现为由低对称性有机阳离子和弱碱性阴离子 (有机/无机) 组成[43]。这类溶剂因其独特的溶解性能, 可有效溶解纤维素、几丁质等难溶性生物大分子, 因而在孢粉素提取中展现出独特优势。离子液体处理法提取孢粉素具体操作为将孢粉悬浮于离子液体中, 置于PTFE密封的玻璃反应器内, 通过平行反应站进行加热处理, 最终经蒸馏水洗涤干燥获得产物[37,44]。应用有采用40%四丁基氢氧化膦水溶液处理油菜蜂花粉[30], 以及直接使用离子液体提取杨树花粉的孢粉素[44]。该方法具有环境友好、操作简便等优点, 不仅能简化纯化步骤, 还能保持孢粉素结构完整性, 去除蛋白质和纤维素组分。但目前该方法制备的孢粉素作为聚合物载体的性能表征尚不充分[45], 有待进一步研究完善。

## 4 孢粉素载药方法

孢粉素作为一种天然原始材料, 凭借其优异的生

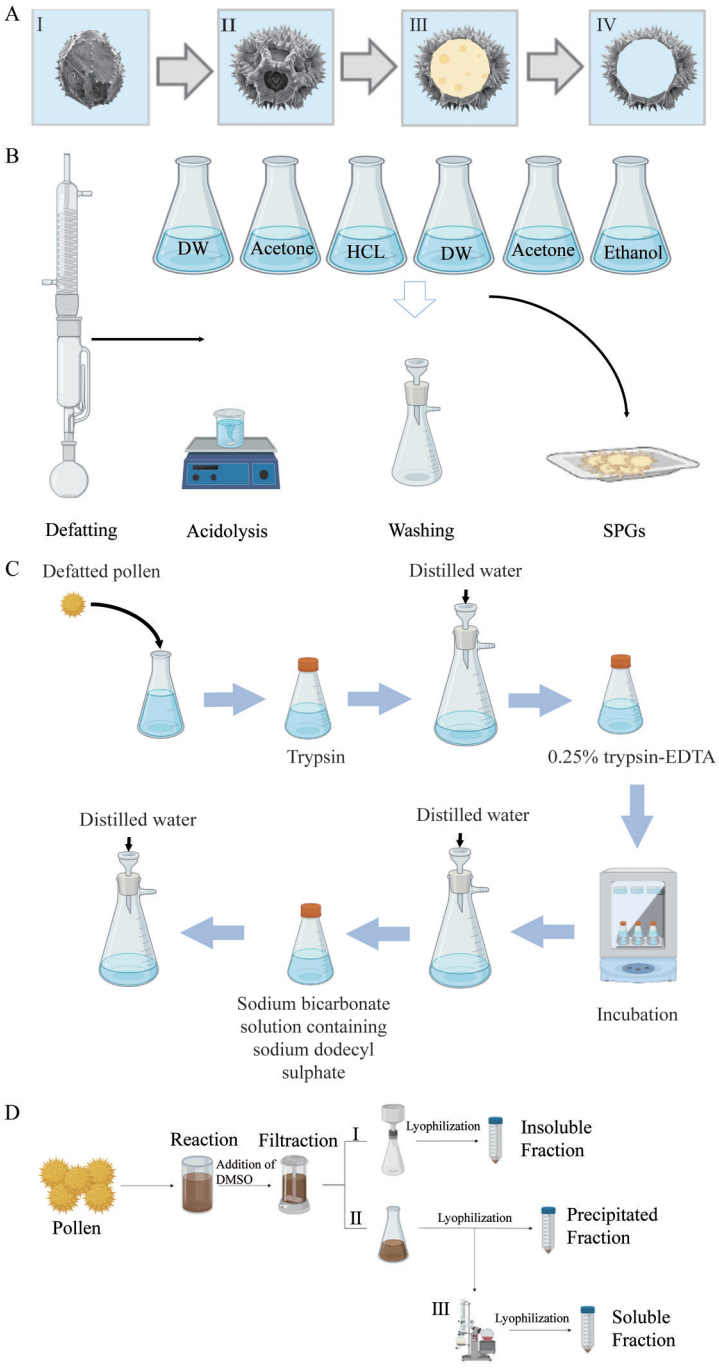



**Figure 2** Schematic diagram of the method for preparing sporopollenin. A: Schematic diagram of the process from primordial pollen to sporopollenin. Adapted from Ref. 3 with permission, copyright 2018 Scientific Reports; B: Schematic diagram of chemical extraction method. Adapted from Ref. 36 with permission, copyright 2024 Journal of Food Measurement and Characterization; C: Schematic diagram of chemical-enzymatic extraction method (Drawn using BioRender.com); D: Schematic diagram of ionic liquid extraction method. Adapted from Ref. 37 with permission, copyright 2025 ACS Omega

物相容性和独特的理化特性，在生物医学领域展现出广阔的应用前景。研究表明，这种天然微囊系统具有来源广泛、无免疫原性、尺寸均一等优势，已成功应用于药物递送、疫苗载体、医学影像等多个领域[46]。因孢粉素微胶囊在控释给药系统中表现突出，其良好的物理化学稳定性、可控的药物释放特性以及可延长肠道滞留时间等特点，使其成为合成生物胶囊的替代品之一[38]。目前，该载体系统已实现对抗肿瘤药物、蛋白质、益生菌等多种活性成分的有效负载。

目前，孢粉素载药方法主要有以下3种：① 依靠药物分子自发渗透实现药物装载的被动加载；② 通过负压促进药物渗透的真空加载；③ 利用外力实现药物填

充的压缩加载。

### 4.1 被动加载

被动扩散载药技术利用亲脂性药物分子的自发渗透特性, 通过孢粉素纳米孔道实现药物装载, 其关键在于维持载药体系的均匀分散性[42]。该方法具有操作简便的优势, 仅需通过物理吸附即可完成载药过程[47]。然而, 该技术存在明显局限性: 一方面药物释放动力学调控能力较弱; 另一方面可能引发潜在的生物相容性风险。

### 4.2 真空加载

真空辅助载药技术在被动扩散基础上引入负压环境, 通过抽真空排出孢粉素内部空气, 显著提升溶液渗透效率。如向日葵花粉装载BSA的过程: 负压促使空气从微孔排出, 从而驱动蛋白溶液的主动渗透[17]。该技术优势突出生物相容性优异, 可同时装载亲/疏水性药物; 载药量较被动扩散显著提高。但工艺参数需要优化, 研究表明, 真空度需控制在临界值以下, 避免药物反渗, 如双氯芬酸钠载药实验显示, 过载真空会导致药物外泄[48]; 载药时间存在最优区间。对比研究证实, 真空辅助法的载药效率显著优于其他方法[49]。

### 4.3 压缩加载

压缩载药法采用液压机将孢粉素压制成片剂后浸入药液, 通过物理压缩促进药物吸收[50]。该方法利用孢粉素外壁的弹性特性, 可实现高浓度药物的高效装载, 且不受纳米级通道限制, 载药体积显著大于被动扩散法。然而, 研究数据表明, 其载药效率存在一定局限: 以5-氟尿嘧啶为例, 压缩法的包封率 (32%) 虽显著高于被动法 (15.5%), 但仍低于真空辅助法 (49%)[49]。该差异可能与压缩过程中部分药物外泄有关, 具体机制有待进一步研究。

鉴于中药领域内各类孢粉之间显著的结构差异性, 需采用不同的处理策略, 以确保其载药效率。此外, 处理前后的孢粉素在载药能力方面亦会展现出明显变化, 处理前药物载药率明显低于处理后药物载药率[3]。药物与孢粉素比例增加, 负载率降低。这可能是由于在较高药物浓度下药物的可用装载位点 (微通道) 减少所致[49]。同一方法负载亲水性药物和疏水性药物对其载药量有些许影响, 以及酸处理和碱处理对其载药量的影响[51]。真空加载时间也会影响其载药率, 时间越长, 负载率越大, 这可能归因于长时间真空应用为负载溶液的水蒸发提供了足够的时间[52]。

孢粉素载药的优势主要在于它们能够加强药物输送和提高生物利用度。首先, 孢粉素具有独特的空囊结构、粒径均匀、孔隙度大、内腔大, 这些特性使其在作为药物载体时能够提供足够的负载空间; 其次, 孢粉素的分散性好, 化学稳定性好, 这使其在药物制剂过程中能保持稳定, 不易被酸、碱、微生物等分解手段破坏; 此外, 孢粉素不溶于大多数有机溶剂, 这增加了其在药物制剂中的适用性。由于这些特性, 孢粉素可以用作不稳定药物或油脂类药物等微胶囊载体。因此孢粉素成为口服给药系统的理想候选微载体。孢粉素微载体还能保护包裹的药物不在胃肠道中降解, 因此具有靶向给药的潜力, 并且孢粉素所携带药物的生物可降解性进一步增强了其作为可持续和环保型给药系统的潜力。

## 5 应用领域

孢粉素作为植物孢粉外壁的天然材料, 可对药物进行掩味[53], 凭借其稳定的物理化学性质及极大的空腔结构为药物提供了一个稳定的微环境增加口服药物的稳定性[14,54-58], 负载药物后表现出一定的缓控释作用[3,17,24,28,39,47,59-65], 孢粉素作为载体也可用于新的智能给药系统[18,66]。此外, 通过表面修饰技术可进一步优化孢粉素载体的性能, 拓展其在智能化药物递送系统中的应用空间[11,36,67,68], 具体应用见表2。

**Table 2** Application of sporopollenin (SP) in drug-carrying. AuNPs: Gold nanoparticles

| Application field | Research content | Ref. |
|---|---|---|
| Taste masking | As a natural carrier, sporopollenin employing dual encapsulation technology can effectively mask the characteristic odor of cod liver oil when the drug-loading ratio (oil-to-sporopollenin) is maintained below 2:1 | [53] |
| Enhanced drug stability | Sporopollenin carriers combined with surface modification and other technologies to improve the stability of active bacteria, combined with pH-responsive controlled release technology and SP-Au sensor substrates to improve the stability of pantoprazole in gastric acid and AuNPs in biosensors | [14,54-58] |
| Sustained and controlled release | The sporopollenin carrier can stably encapsulate some conventional drugs, anti-tumour drugs and biomolecules, and has good slow and controlled release performance after encapsulation | [3,17,24,28,39, 47,59-65] |
| Smart drug delivery | Sporopollenin, with its unique spike structure and technologies such as W/O/W emulsion loading and micromotors, is a new solution for smart drug delivery that significantly enhances retention and delivery efficiency | [18,66] |
| Surface modification | Functionalized modification of sporopollenin optimizes its adhesion, stability and resistance to degradation. Sporopollenin was modified with sodium alginate to mask odour; complex reconstitution with column aromatic molecules increased delivery efficiency and bioactivity | [11,36,67,68] |

## 6 展望

孢粉素的研究与应用仍面临诸多挑战与机遇。在质量评价方面, 缺少系统的表征评价体系, 可借助多学科交叉手段, 如结合光谱分析、分子动力学模拟等技术, 系统探究孢粉素的理化性质与构效关系, 明确其在不同生理环境下的稳定性与降解机制, 为其作为药物或生物制剂的开发提供坚实理论基础。同时, 运用分子生物学、化学生物学等前沿技术, 解析孢粉素与药物分子相互作用的分子机制, 从纳米尺度揭示其靶向识别与控释规律, 助力设计更高效、精准的靶向给药系统。

工艺开发领域, 亟待突破现有制备技术瓶颈。一方面, 需建立普适性的孢粉素提取标准流程, 探索不同来源孢粉的共性提取规律, 减少方法选择的盲目性; 另一方面, 加大绿色提取技术研发力度, 如开发低毒、可循环的新型溶剂体系, 结合物理辅助技术 (超声、微波) 缩短制备周期, 降低能耗与污染, 推动孢粉素制备工艺向环保、高效、规模化方向发展。

在中医药融合方向, 目前关于孢粉载药应用的研究均集中在载药率提升及表面修饰等应用上, 未深入研究孢粉掏空后孢粉素微载体的药效物质基础与作用机制, 应结合现代药理研究方法, 验证其是否保留原药材活性成分与药理作用。同时, 基于中医配伍理论, 探索孢粉素微载体与负载药物间的协同增效或减毒作用, 或可构建“载体–药物”一体化的新型递药体系, 为中药现代化提供创新思路与技术支撑。此外, 还需完善孢粉素微胶囊的质量评价体系, 建立涵盖生物安全性、载药性能、靶向效率等指标的综合评价标准, 加速其从实验室研究向临床应用的转化进程。

**作者贡献**: 刘艳玲负责文章的文献调研和撰写; 罗晓健、饶小勇、付小明、彭佩雨、张尧负责指导论文及修改; 刘微负责文章整体思路的提出、设计和修改。

**利益冲突**: 本文所有作者声明不存在利益冲突关系。

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