

外用防脱育发类活性成分与纳米载体在洗护发产品中的创新应用

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摘 要

脱发已成为影响全球数亿人身心健康的问题, 其中雄激素性脱发(AGA)是最常见的类型。目前经药监部门批准的外用防脱发活性成分局限于米诺地尔、亚美尼斯(Aminexil)等少数几种药物, 其溶解度低、经皮渗透差、毛囊靶向性不足及长期使用依从性欠佳, 治疗效果存在明显局限。近年来, 植物源活性成分因多靶点作用和低副作用而受到广泛关注, 但其透皮性能同样面临挑战。纳米递送技术的快速发展为解决上述问题提供了新的策略。脂质纳米载体(固体脂质纳米粒、纳米结构脂质载体)、介孔二氧化硅纳米粒、聚合物纳米粒、纳米脂质体及纳米微乳等系统, 通过独特的物理化学性质实现了活性成分的毛囊靶向递送、缓释控释和透皮效率提升。本文系统综述了现有外用防脱育发活性成分的分类与作用机制, 深入解析各类纳米载体在经皮递送中的优势及其在洗护发产品中的转化应用现状, 并在此基础上展望了该领域未来的研发方向。

关键词

防脱发, 育发, 纳米载体, 毛囊靶向, 洗护发产品, 经皮递送

Innovative Applications of Topical Anti-Hair Loss and Hair Growth Active Ingredients and Nanocarriers in Hair Care Products

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Abstract

Hair loss has become a global issue affecting the physical and mental health of hundreds of millions of people, among which androgenetic alopecia (AGA) is the most common type. At present, the topical anti-hair loss active ingredients approved by drug regulatory authorities are limited to a small number of drugs such as minoxidil and aminexil. These ingredients suffer from low solubility, poor transdermal penetration, insufficient hair follicle targeting, and unsatisfactory long-term use compliance, leading to obvious limitations in therapeutic efficacy. In recent years, plant-derived active ingredients have attracted extensive attention due to their multi-target effects and low side effects, but they also face challenges in transdermal permeability. The rapid development of nanodelivery technologies has provided new strategies to solve the above problems. Lipid nanocarriers (solid lipid nanoparticles, nanostructured lipid carriers), mesoporous silica nanoparticles, polymeric nanoparticles, nanoliposomes, nanoemulsions and other systems have achieved hair follicle-targeted delivery, sustained and controlled release, and improved transdermal efficiency of active ingredients through their unique physicochemical properties. This paper systematically reviews the classification and mechanism of action of existing topical anti-hair loss and hair growth active ingredients, deeply analyzes the advantages of various nanocarriers in transdermal delivery and the current status of their translational applications in hair care products, and prospects the future research and development directions in this field on this basis.

Keywords

Anti-Hair Loss, Hair Growth, Nanocarriers, Hair Follicle Targeting, Hair Care Products, Transdermal Delivery

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1. 引言

脱发是一种常见的皮肤附属器疾病，全球范围内影响人群极为广泛。一项针对中国六个城市 18 岁以上居民的调查显示，男性雄激素性脱发(AGA)的患病率为 21.3%，女性为 6.0% [1]。AGA 并非单纯的“掉头发”，而是在遗传背景作用下，毛囊对雄激素(尤其是二氢睾酮，DHT)产生异常敏感反应，导致毛囊微型化蜕变的过程：原本粗壮的终毛逐渐转变为细软的毳毛，直至毛囊萎缩、失去生发能力。除 AGA 外，斑秃、休止期脱发及化疗诱导性脱发等多种脱发类型也给患者带来显著的心理和社会经济负担。

AGA 的经典治疗药物包括外用米诺地尔和口服非那雄胺[1]，目前，现有疗法的局限性日益凸显：米诺地尔存在水溶性差、皮肤渗透率低、长期使用可致接触性皮炎等问题；口服非那雄胺可能引起性功能障碍等全身性副作用。并且，即使坚持用药，仍有相当比例的患者对标准疗法应答不佳或出现病情复发。天然植物提取物因其多靶点作用的独特优势和较低的毒副作用，在防脱育发领域吸引研究者的广泛兴趣。咖啡因、锯叶棕提取物、迷迭香油、槲皮素、白藜芦醇等活性成分在抑制 5 α -还原酶、抗氧化、抗炎及促进毛乳头细胞增殖等方面展现出良好潜力。然而，多数植物活性成分面临溶解度差、透皮屏障通过效率低等共性挑战，制约了其临床效用的充分发挥。

纳米载体(粒径通常在 1~1000 nm)凭借其独特的尺寸效应和表面可修饰性，能够显著改善难溶性活性成分的水溶性和化学稳定性，增强透皮和毛囊渗透效率，并实现靶向递送和缓释控释[2]。2024~2026 年

间,SCI 期刊涌现了大量关于纳米递送系统在防脱头发领域的研究报道,涵盖纳米结构脂质载体、固体脂质纳米粒、介孔二氧化硅纳米粒、壳聚糖纳米粒、纳米微乳及外泌体样囊泡等多种体系。以生物相容性脂质分子构建的纳米载体,不仅提升了米诺地尔、非那雄胺等传统药物的毛囊靶向性,也极大地拓展了天然活性成分的应用范围。

本文围绕“外用的防脱育发类活性成分与纳米载体在洗护发产品中的创新应用”这一主题,系统回顾上述领域的研究现状与进展,梳理各类活性成分的作用机制,阐述纳米载体的优势与瓶颈,展望未来研发方向,以期新型防脱育发产品的开发提供系统性的学术参考。

2. 脱发的病理生理机制与治疗靶点

毛囊(HFs)在人体皮肤中起着至关重要的作用,能提供保护、感知和体温调节功能[3]。正常的毛发周期包括三个重要阶段:生长期、退行期和休止期[4]。在某些情况下,毛发周期可能会受到多种因素的影响,从而导致脱发。如由免疫因素引起的脱发称为斑秃(AA),由激素变化引起的脱发称为雄激素性脱发(androgenetic alopecia, AGA) [5]。化疗和某些药物可能会导致生长期脱发,压力也是导致脱发的重要原因之一,称为休止期脱发[6]。AGA 和 AA 是不可逆转的,其中 AGA 是最常见的脱发类型,据统计约占 50% 的老年男性和 15% 的绝经后女性受到影响[7]。

AGA 的发病机制涉及遗传易感性、雄激素代谢紊乱及毛囊微环境改变等多重因素的复杂交互。遗传因素决定了特定区域毛囊对雄激素的敏感程度。在 5 α -还原酶的作用下,睾酮被转化为活性更强的 DHT,其与雄激素受体的结合能力远高于睾酮本身,更容易诱发 AGA [8]。

此外,毛囊周围的微循环障碍、氧化应激、炎症因子的浸润以及细胞凋亡的异常激活,也共同参与了 AGA 的病理进程[9]。DHT 不仅能直接缩短毛囊的生长周期,还能够通过诱导毛囊细胞中活性氧(ROS)的生成,触发细胞凋亡。ROS 和细胞凋亡进一步诱导炎症反应,损伤毛囊和毛周血管,形成恶性循环,不断加剧毛囊的破坏进程。头皮微环境的慢性低度炎症、毛周毛细血管网的减少和微循环障碍,都与脱发的进展密切相关[10]。

基于上述多因素发病机制,可通过多靶点协同干预,实现防脱育发策略:降低 DHT 水平或阻断其受体结合、清除 ROS 减轻氧化损伤、抑制炎症因子的过度释放、促进毛周血管新生以改善营养供给等。

3. 外用防脱育发活性成分的分类与研究进展

3.1. 经典化学合成药物

米诺地尔是目前全球应用最广的外用脱发治疗药物。作为一种钾通道开放剂和血管扩张剂,米诺地尔通过改善毛囊区域的局部血流,延长毛囊生长期,促进毛发再生[11]。然而,米诺地尔存在显著的应用局限:水中溶解度低导致外用制剂的透皮性能不佳,易于经皮渗透进入体循环而引发面部多毛症等副作用[12]。

非那雄胺可通过不可逆地与 5 α -还原酶结合,阻止睾酮转化为 DHT 来减轻脱发症状。但由于分子量较大且经皮吸收率有限,毛囊中有效药物浓度难以达到治疗阈值。

目前,米诺地尔和非那雄胺是美国食品药品监督管理局(FDA)批准仅有的 2 种治疗脱发的药物[13],但可能存在过敏性接触性皮炎、头皮刺激、性功能障碍或抑郁症等不良反应[14] [15]。

亚美尼斯(Aminexil)是用于治疗脱发的非激素类药物之一,可通过扩张发根血管、提升毛囊氧气与营养供给,激活毛囊并抑制毛囊微型化;同时通过抑制赖氨酰羟化酶 mRNA 表达,软化毛囊周围硬化胶原、阻止毛囊周围纤维化,从根源减少脱发并促进毛发再生[16] [17]。相较于米诺地尔,Aminexil 安全性更高,更适用于男女雄激素性脱发、化疗性脱发等场景[18]。但 Aminexil 具有强亲水性,难以穿透头皮角质层

脂质屏障，经皮渗透效率低、难以靶向抵达毛囊，传统制剂生物利用度不足，限制其防脱育发功效发挥[19]。

3.2. 天然植物提取物

植物源防脱活性成分是近年来毛发健康研究领域的热点方向之一。相较于化学合成类药物，天然产物通常具备多靶点作用特点，且整体毒性更低，目前在洗护发产品的开发中已有大量应用，其中应用最为广泛的天然植物提取物主要是侧柏叶、何首乌、人参等，其主要成分和防脱的作用机制见表 1。

Table 1. Major active components and mechanisms of action of natural plants for hair loss prevention
表 1. 天然防脱植物的主要成分及作用机制

中药材	主要成分	作用机制
侧柏叶	萜类、黄酮类等	激活 Wnt/ β -连环蛋白、Akt/GSK3 β 等相关信号通路，上调多种毛发生长因子表达，促进血管生成以改善毛囊血供
		降低 5 α -还原酶表达与 DHT 水平、减轻氧化应激损伤，促使毛囊提前进入生长期并延长生长周期[20]
何首乌	二苯乙烯苷等天然多酚类	调节 Wnt/ β -catenin 信号传导能够促进毛囊干细胞(HFSCs)的增殖和分化，促进毛发周期的开始，促进毛发周期的开始[21]
		可促进毛干产生及增强毛干角蛋白表达，且能够将生长期的毛囊维持在毛囊周期的最大增殖阶段[22]
人参	人参皂苷、人参炔醇	通过促进毛乳头细胞与外根鞘角质形成细胞增殖、抑制细胞凋亡，激活 Wnt/ β -连环蛋白、PI3K/Akt 等信号通路，刺激毛囊由休止期进入生长期并延缓退行期[23]
		上调 VEGF、IGF-1 等生长因子表达，增强毛囊自噬、减轻氧化应激与细胞衰老，抑制 DHT 诱导的雄激素受体升高，发挥抗雄激素作用[24] [25]
锯棕榈	油酸、亚油酸等不饱和脂肪酸	减少皮脂分泌、抑制痤疮丙酸杆菌以减轻头皮炎症[26]
		临床研究表明含人参提取物的外用制剂可有效改善毛发数量与质量，效果与米诺地尔相近且安全性良好[27]。
		通过抗雄激素、激活 β -连环蛋白通路、促进血管生成、抗炎和抗氧化应激改善 AGA 毛囊状态，对 DHT 生成的抑制作用比合成药物更温和，且几乎无全身性副作用

此外，槲皮素、积雪草、当归、白藜芦醇[28]、迷迭香油、水飞蓟提取物、鱼腥草提取物[29]等也通过不同机制在防脱育发领域得到关注。

3.3. 现有活性成分应用的主要瓶颈

然而，上述各类防脱育发类活性成分在洗护发产品中的实际应用中面临三个核心问题：一，多数天然活性成分在水中溶解度极低(如槲皮素、白藜芦醇、锯叶棕油)或化学稳定性差，常规配方中的溶解困难，在存储过程中析出或降解；二，皮肤角质层是自然形成的致密屏障，粒径小于 500 nm 且具有一定脂溶性的分子才能有效透过，而上述多数活性成分的透皮性能不佳，导致毛囊部位蓄积含量低，难以实现临床药效；三，洗护发产品(洗发水、护发素等)在头皮上的停留时间极短(通常仅 2~5 分钟)，活性成分难以在极短的时间内实现从产品基质到毛囊的迁移和渗透。因此如何精准、高效地将活性成分递送至毛囊并延长其作用时间，是解决现有应用难点的关键。

4. 代表性纳米载体的类型与研究进展

毛囊是防脱发活性成分经皮递送的重要天然通路，其开口无连续角质层，可使成分直接抵达毛囊上

皮与毛乳头。依托粒径效应、表面电荷调控、脂质相容性、缓释长效滞留四大核心机制，各类纳米载体能够显著提升毛囊靶向递送效率：适宜粒径(200~700 nm)的纳米颗粒可顺利穿透毛囊狭窄通道，实现定向渗透[30]；通过调控表面电荷或进行功能修饰，可借助静电作用与配体识别增强毛囊特异性结合[31]；脂质类载体可适配毛囊周边富脂质微环境，助力活性成分释放扩散[32]；同时纳米载体具备缓释特性，能延长成分在皮肤的滞留时间、提升透皮总量，弥补普通外用制剂易被清洗、作用时效短的不足[33]。基于上述优势，不同类型纳米载体在防脱发经皮递送领域得到广泛探索与应用，相关研究也取得诸多进展[34]，详见表 2。

Table 2. Cross-comparison of key performance indicators of major nanocarriers for hair loss prevention and hair growth
表 2. 主要防脱发发纳米载体的关键性能指标横向对比

纳米载体类型	代表性粒径范围	载药量与包封率	物理稳定性	生产成本	毛囊靶向效率
固体脂质纳米粒(SLN) [59]	50~1000 nm	包封率 65%以上；载药量受限于脂质结晶度高	贮存期间药物易泄漏；结晶导致载药量下降	中等(固态脂质 + 常规乳化剂)	可通过粒径调控实现毛囊富集
纳米结构脂质载体(NLC) [60]	100~600 nm (最佳约 400 nm)	包封率：29.68%~92.48%；引入液态脂质后载药量提升	优于 SLN，晶格缺陷减少药物泄漏；体内半衰期较短、磷脂易氧化	中等偏高(需多种脂质 + 均质工艺)	300 nm NLC 毛囊蓄积最佳；400 nm 颗粒在人体毛囊中 7 天仍可检出
介孔二氧化硅纳米粒(MSN)	可调(100~500 nm 级)	高比表面积 + 中空空腔，载药量显著高于脂质载体	热稳定优异，但无机材料柔韧性不足	较高(需硅源 + 模板剂 + 高温煅烧)	可表面修饰增强靶向
聚合物纳米粒(PLGA/壳聚糖)	100~300 nm 级	包封率较高，降解速率可调	聚合物骨架可设计为缓释数月；壳聚糖修饰后黏性高、皮肤保留率提升	中等(生物可降解聚合物)	配体修饰可主动靶向
脂质体/囊泡 [32]	50~500 nm；非离子囊泡可达 1292 nm	亲水/疏水双室包载	磷脂易氧化，稳定性挑战大	较高(高纯度磷脂)	角质层相容性好
纳米微乳	<100 nm (热力学稳定)	亲脂性药物溶解度高	热力学稳定，可避免固体颗粒沉降	较低(常规乳化工艺)	W/O 型微乳经毛囊完整结构吸收
纳米晶	200~300 nm	100%载药(无额外载体)	需防重结晶，长期稳定挑战大	低(湿法研磨，工艺简便)	粒径可设计为毛囊通道适配

4.1. 固体脂质纳米粒与纳米结构脂质载体

固体脂质纳米粒(SLN)是目前研究最为深入的脂质纳米载体之一。SLN 以固态脂质为主要基质，活性成分被物理包埋或被溶解于固体脂质骨架中。由于脂质组分与皮肤角质层的脂质结构高度相似，SLN 可显著增强活性成分的角质层渗透效率。将非那雄胺负载于磷脂酰胆碱和三甲基壳聚糖修饰的 SLN 后，显著提升了皮肤保留和毛发生长效果[35]。此外，SLN 包载氟他胺可提高渗透率，既能实现氟他胺在毛囊部位的缓释与控释，又能增强其在发干中的沉积，促进毛囊新生，可用于治疗雄激素性脱发(AGA) [36]；以野葛根为原料制备的 SLN 护发喷雾，经体外皮肤渗透与沉积实验证实，可显著提高原料的渗透效果[37]；罗红霉素(ROX)因具备抗凋亡特性可用于毛发再生，其 SLN 作为毛囊靶向系统，具有稳定性好、无刺激性、渗透性佳的优势，可富集于毛囊处，适用于治疗雄激素性脱发或痤疮[38]。

纳米结构脂质载体(NLC)作为第二代脂质纳米载体,是在 SLN 的表面进行修饰,如聚合物涂层(增强载体稳定性)、靶向配体修饰(提升毛囊特异性识别能力)以及表面电荷调控,可进一步优化其性能[39]。NLC 的制备原理在于向固态脂质中引入一定比例的液态脂质,从而破坏固态脂质的有序结晶网络,诱导形成大量不规则晶格缺陷。这些晶格缺陷区域为活性成分提供了额外的结合位点,显著提高了载药量与包封效率,同时有效抑制了储存过程中因活性成分结晶析出所引发的物理不稳定性[40]。并且 NLC 的脂质基质通常为油性成分,还可以促进皮肤渗透,提高渗透率。载非那雄胺的 NLC 在 AGA 模型大鼠中显著增加了毛囊活性毛球数量,且未检测到全身性吸收,表明 NLC 不仅提升了局部药效,还因避免活性成分进入体循环而彻底规避了非那雄胺口服制剂的全身性副作用[41]。体外毛囊递送研究表明,米诺地尔与拉坦前列素共负载于 NLC 后,二者的递送效率均显著提高。其中,拉坦前列素的毛囊递送效率较对照组提升 3 倍,米诺地尔则提升 1.4 倍[42]。此外,采用 Pluronic F127 稳定的 NLC 分别负载薰衣草精油与茶籽油后,所得制剂的粒径分别为 165 nm 和 181 nm, Zeta 电位结果表明其具有优异的静电稳定性。在大鼠模型中,薰衣草油 NLC 组与茶籽油 NLC 组的毛干长度分别较安慰剂组增加 120%和 132%,而市售对照产品的相应增幅仅为 116% [43]。此外还有研究表明, NLC 可作为白藜芦醇的有效递送平台,与头皮冷却疗法联合应用,协同缓解化疗所致的毛囊细胞毒性[44]。

4.2. 介孔二氧化硅纳米粒与杂化纳米系统

介孔二氧化硅纳米粒(MSN)因具有高比表面积、有序介孔结构、优良的热稳定性和可功能化修饰的丰富表面化学位点而备受青睐。中空介孔二氧化硅纳米粒(HMSN)在 MSN 的基础上进一步扩展了内部空腔容积,能够承载更大量的活性成分。通过利用不同粒径的中空介孔二氧化硅纳米粒(HMSN)负载非那雄胺(FNS),与卡波姆水凝胶混合制成 F@H/Gel 局部外用制剂,在 AGA 小鼠模型中显著加速毛发再生,同时还能减少全身副作用[45]。

4.3. 聚合物纳米粒与壳聚糖纳米粒

聚合物纳米粒具有良好的生物相容性、可生物降解性和表面多功能修饰性。壳聚糖是其中研究最为深入天然聚合物之一。Mohamad 等将米诺地尔包封于非离子表面活性剂囊泡中,进一步负载于壳聚糖纳米粒,并复合芦荟提取物,构建了 Cs@Alo/Nio-Mxd 纳米复合递送系统,以实现米诺地尔在头皮部位的缓释行为。动物实验结果表明,该制剂组的皮肤厚度、毛囊总数、毛囊直径及毛囊诱导百分比等组织学参数均显著优于对照组,提示该纳米复合系统能够有效弥补米诺地尔透皮吸收率低及长期用药所致局部刺激性等局限性[46]。

4.4. 脂质体、囊泡与微乳

脂质体是最早应用于化妆品领域的纳米载体之一,其外用最大优势在于其磷脂组分与生物膜的高相容性,几乎不引起皮肤刺激和过敏反应。采用二氨基嘧啶氧化物(乌诺地尔)与多种天然植物提取物复配,可以形成具有高稳定性和安全性的纳米脂质体包载体系[47]。

植物源细胞外囊泡(PDEVs)由脂质双层构成,直径通常在 30~500 nm,天然携带蛋白质、小 RNA 和植物次生代谢物等生物活性分子[48]。相较于哺乳动物来源囊泡,植物源囊泡具有可再生、无病原体风险、口服兼容性好等突出优势[49]。

何首乌来源的外泌体样纳米颗粒(PMENs)可通过小窝蛋白介导的内吞途径进入人毛囊真皮乳头细胞,其携带的 aof-miR168a 和 osa-miR164a 等植物源 miRNA 能够跨物种靶向并沉默人类雄激素受体基因,开创了“RNA 纳米药物”治疗脱发的全新路径[50]。此外,侧柏叶来源的细胞外囊泡(PO-EVs)兼具抗炎、

抗氧化和促血管生成的天然活性,与米诺地尔纳米颗粒共递送时可协同改善毛囊微环境[51]。积雪草细胞外囊泡作为一类植物源天然纳米囊泡,其包载生长因子(rIGF-1 和 rFGF-7)后应用于头皮精华产品,56 天临床研究显示出良好的生发和头皮健康改善效果[52]。

微乳体系由于粒径通常小于 100 nm 且热力学稳定,在透皮递送方面具有天然优势。迷迭香油基微乳共递送槲皮素和腺苷(QAR ME)粒径仅 24.98 nm,在 AGA 病理模型中同时实现了抗氧化、抗炎、促血管新生和激活 Wnt/ β -catenin 通路的协同效应,且 28 天连续外用无不良反应[53]。该研究证实,微乳不仅能改善活性成分的溶解度,还能利用油脂本身的药理活性参与治疗过程,这为天然植物油基纳米载体的设计提供了新思路。

4.5. 其他新型纳米载体

近年来,以纳米晶、智能响应型载体和微针技术为代表的新兴递送系统,为防脱育发领域带来了突破性进展。

纳米晶技术采用自上而下的湿法研磨工艺,可将难溶性药物粉碎至纳米级别,该方法无需额外载体、工艺简便,更适合工业化生产。以甘油酸为稳定剂制备的槲皮素纳米晶,粒径稳定在 200~300 nm 且分布均匀,在经皮递送与雄激素性脱发(AGA)干预中效果突出。研究显示,毛囊靶向型槲皮素纳米晶的体外累积渗透量、皮肤滞留量分别较原料药提升 2.27 倍、2.47 倍,还可有效降低二氢睾酮(DHT)诱导 AGA 模型局部的 DHT 含量;而槲皮素与甘草酸共研磨制得的纳米晶,也证实了纳米晶技术应用于 AGA 治疗的可行性[54]。

智能响应型载体可根据毛囊微环境的特定信号触发药物释放。金属有机框架(MOF)纳米载体经硬脂酸表面修饰后,不仅在水性环境中保持结构稳定,还可利用硬脂酸本身的 5 α -还原酶抑制活性协同促进毛发生长[55]。基于环糊精的 MOF 体系具备化学可调性、高载药量和良好生物相容性,可通过刺激响应机制实现活性成分的按需释放。

微针技术为突破皮肤角质层屏障提供了微创解决方案。透明质酸基可溶性微针负载侧柏叶提取物后,机械强度可达 3.5 MPa,能够穿透角质层直达真皮层,通过“机械刺激-药物协同”双重作用显著促进毛囊再生(毛发密度提升 228%) [56]。黄芩素纳米晶联合微针递送系统可将黄芩苷溶解度提升 30 倍、透皮效率提高 6.93 倍,每 3 天给药一次即达到与每日使用米诺地尔相当的疗效[57]。HDAC1 过表达纳米囊泡负载于可溶解微针后,可在毛囊微环境中实现 10 天长效缓释,单次应用效果优于连续 21 天外用米诺地尔[55]。脂质体共包载人参皂苷 CK 和一氧化氮供体(GSNO)的微针系统,通过抑制炎症因子、清除活性氧和促进血管新生,为毛乳头细胞增殖提供有利微环境,转录组学证实其可激活 PI3K-AKT 信号通路上调 β -catenin 表达[58]。

5. 纳米载体在洗护发产品中的应用局限与未来展望

将纳米载体应用于洗护发产品,可有效解决传统外用防脱育发产品活性成分溶解度低、经皮渗透性弱、毛囊靶向性差等痛点。依托粒径效应、表面电荷调控、脂质相容性及缓释特性,纳米载体能显著提升活性成分在毛囊的富集度与作用效果,是洗护产品功效升级的核心技术方向。不过该技术从实验室走向产业化,仍存在一定应用局限,同时具备广阔的发展前景。

目前产业化应用的核心局限主要集中在四个方面:一是配方兼容性较差,洗护体系中大量阴离子表面活性剂易破坏脂质类纳米载体结构,叠加体系 pH 值波动,易造成载体破损、活性成分泄漏,是配方研发的首要难题。二是产品储存稳定性不足,纳米颗粒长期存放易团聚、沉降,负载的活性成分易氧化降解,纳米晶易出现重结晶问题,即便稳定性优异的纳米结构脂质载体(NLC)也难以完全规避。三是原料成

本与供应受限, 纳米载体制备所需的高纯度磷脂、特种脂质等高端辅料价格高、获取难度大, 大幅提升生产成本, 制约技术规模化推广。四是合规与应用门槛高, 各国对化妆品纳米材料有严格的安全评估、申报注册要求, 审批流程繁琐; 且冲洗型洗护产品与头皮接触时间短, 纳米载体难以高效完成毛囊递送, 实际使用效果受限。

针对上述痛点, 行业已形成成熟的优化方案: 通过聚合物修饰改性纳米粒[61]、选用耐表面活性剂的载体材料, 或采用活性成分后添加工艺, 改善配方兼容性; 对易失活的活性成分采用冻干预处理、使用前复溶的方式, 延长产品货架期; 通过优化载体配比、精简冗余辅料, 搭配植物油等天然低成本原料替代高端合成辅料[62], 实现降本增效, 助力技术规模化应用。

长远来看, 纳米载体洗护技术将实现多维度迭代升级。首先, 实现活性物复配与协同增效。单一活性成分难以覆盖 AGA 多靶点病理机制, 复方策略已成共识。未来应重点探索化学药物与植物提取物的协同配伍, 例如阳离子纳米乳共递送米诺地尔与非那雄胺, 通过抑制 5α -还原酶、激活 β -catenin 和 VEGF 通路实现微环境重编程, 同时利用表面正电荷增强毛囊滞留并降低全身暴露[63]。中药复方与天然活性物的联用亦具前景——侧柏叶 EVs 与米诺地尔纳米颗粒共递送可通过抗炎抗氧化与促毛囊活化的互补机制提升疗效可持续性[51]。多靶点协同的“鸡尾酒”式递送策略将是突破现有疗效天花板的关键。第二, 实现载体功能化与精准靶向。下一代纳米载体的核心竞争力在于“智能”属性。毛囊微环境响应型载体可实现按需释药——针对 AGA 毛囊周围基质金属蛋白酶(MMPs)过表达、pH 异常或氧化应激增高等病理特征, 设计酶响应、pH 响应或 ROS 响应的纳米系统, 使活性成分仅在病变部位大量释放, 减少对健康组织的非特异性暴露[64]。第三, 发展物理促渗技术与纳米载体联用。微针、离子导入、超声导入等物理促渗手段与纳米载体的深度融合, 有望系统性解决洗护产品作用时长短、透皮效率低的行业痼疾。其中可溶解微针与纳米载体的一体化设计最具转化前景: 微针穿刺形成的微通道为纳米颗粒提供直达真皮和毛囊的“绿色通道”[55], 而纳米载体则赋予活性成分缓释和靶向能力, 二者协同可实现“一次操作、长效作用”的临床效果。

随着纳米载体技术、植物活性成分作用机制研究及微针等物理促渗技术的持续成熟, 安全、高效、体验感优异的纳米型防脱育发产品将不断落地。特别是植物源外泌体样纳米囊泡等兼具低免疫原性和天然生物活性的载体, 有望成为毛囊精准递送的核心平台, 为脱发人群提供精准、多元化的洗护解决方案。

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