[DOI]10.12016/j.issn.2096-1456.202550077

·综述·

纳米抗菌材料在根管治疗中的研究进展

王依依[1]，　秦璐[1]，　贾言敏[1]，　杜旭硕[1]，　刘飞[2]，　王素苹[2]
1.郑州大学口腔医学院，河南 郑州（450006）；　2.郑州大学第一附属医院口腔内科，河南 郑州（450052）

【摘要】 根管治疗作为牙髓及根尖周疾病的核心治疗手段，其疗效高度依赖于抗菌药物的有效性。临床常用的氢氧化钙、氯己定及抗生素糊剂等传统药物虽在感染防控方面发挥了一定作用，但各自存在明显局限性：影响牙本质机械性能、对坏死组织溶解能力不足、易引发菌株耐药等，难以达到理想的有效性和安全性。传统大分子根管药物也面临根管系统复杂性的挑战。近年来随着材料学的飞速发展，新型抗菌剂崭露头角。以银纳米颗粒、氧化锌纳米颗粒为代表的金属纳米材料因其独特的理化性质和优越的抗菌性被广泛应用于医学领域。壳聚糖纳米颗粒有着优越的生物安全性，氢氧化钙纳米颗粒弥补了传统氢氧化钙制剂的局限，季铵聚乙烯亚胺纳米颗粒可赋予现有口腔材料抗菌性能。运用纳米递送系统，如介孔硅酸钙和介孔二氧化硅搭载抗菌分子的新型抗菌纳米颗粒在抗生物膜、生物安全性、促进组织修复等方面具有显著优势，还能减少耐药问题的出现，相较于传统的根管消毒药物有良好的应用前景。纳米技术的突破为根管治疗药物的革新提供了全新的方向。因此本文就纳米抗菌材料在根管治疗中的研究进展进行综述。

【关键词】 牙髓病；　根尖周病；　根管治疗；　抗菌纳米颗粒；　金属纳米颗粒；　银纳米颗粒；　氧化锌纳米颗粒；　壳聚糖纳米颗粒；　氢氧化钙纳米颗粒；　季铵聚乙烯亚胺纳米颗粒；　纳米递送系统；　介孔硅酸钙纳米颗粒；　介孔二氧化硅纳米颗粒

【中图分类号】 R78　**【文献标志码】** A　**【文章编号】** 2096-1456（2025）08-0699-10

【引用著录格式】 王依依，秦璐，贾言敏，等．纳米抗菌材料在根管治疗中的研究进展[J]. 口腔疾病防治，2025, 33(8): 699-708. doi:10.12016/j.issn.2096-1456.202550077.

微信公众号

Research progress on nano-antimicrobial materials in root canal therapy

WANG Yiyi[1], QIN Lu[1], JIA Yanmin[1], DU Xushuo[1], LIU Fei[2], WANG Suping[2]　1. School of Stomatology, Zhengzhou University, Zhengzhou 450006, China;　2. Department of Stomatology, The First Affiliated Hospital of Zhengzhou University, Zhengzhou 450052, China
Corresponding author: WANG Suping, Email: wangsupingdent@163.com

【Abstract】 The efficacy of root canal therapy, as a core intervention for endodontic and periapical diseases, is highly dependent on the effectiveness of antimicrobial drugs. Although traditional drugs such as calcium hydroxide, chlorhexidine, and antibiotic pastes commonly used in the clinic play a role in preventing and controlling infections, they have obvious limitations. These drugs influence the mechanical properties of dentin, insufficiently solubilize necrotic tissues, and are susceptible to bacterial resistance, which makes achieving the desired effectiveness and safety difficult. Traditional macromolecular root canal drugs also face the challenge of the complexity of the root canal system. With the rapid development of material science in recent years, new antimicrobial agents have emerged. Metallic nanomaterials such as silver nanoparticles and zinc oxide nanoparticles are widely used in the medical field due to their unique physicochemical properties and superior antimicrobial properties. Chitosan nanoparticles have superior biosafety, calcium hydroxide nanoparticles compensate for the limitations of traditional calcium hydroxide formulations, and quaternary ammonium polyethyleneimine nanoparticles can confer antimicrobial properties to existing oral materials. Novel antimicrobial nanoparticles using nano-delivery systems, such as mesoporous calcium silicate and mesoporous silica, carry anti-

【收稿日期】2025-02-26；　**【修回日期】**2025-05-07
【基金项目】河南省医学科技攻关计划省部共建重点项目（SBGJ202102162），河南省教育厅高等学校重点科研项目（22A320006）
【作者简介】王依依，硕士研究生在读，Email: 503421838@qq.com
【通信作者】王素苹，副主任医师，博士，Email: wangsupingdent@163.com

microbial molecules with significant advantages in terms of anti-biofilm, biosafety, and promotion of tissue repair. Further, these agents reduce drug resistance, which improves prospects for application compared to traditional root canal disinfection drugs. The breakthrough of nanotechnology provides a novel direction for the innovation of root canal treatment drugs. Therefore, this paper reviews the research progress of nano-antimicrobial materials in root canal therapy.

【Key words】 endodontic disease; periapical disease; root canal therapy; metal nanoparticles; antimicrobial nanoparticles; silver nanoparticles; zinc oxide nanoparticles; chitosan nanoparticles; calcium hydroxide nanoparticles; quaternary ammonium polyethyleneimine nanoparticles; nano-delivery systems; mesoporous calcium silicate nanoparticles; mesoporous silica nanoparticles

J Prev Treat Stomatol Dis, 2025, 33(8): 699-708.

【Competing interests】 The authors declare no competing interests.

The study was supported by Henan Provincial Medical Science and Technology Research Plan Provincial Key Project (No. SBGJ202102162); Henan Provincial Department of Education Key Scientific Research Project of Higher Education Institutions (No. 22A320006).

纳米材料是指其三维结构中至少有一维处于纳米级别(1～100 nm)的材料,当材料尺寸进入纳米范畴,特殊的结构使其突破传统大分子抗菌材料的边界,表面原子占比的显著提升赋予了纳米材料极高的机械强度和功能可设计性[1]。传统根管治疗面临根管结构复杂、顽固细菌清除困难、牙本质机械性能易受影响等问题。新型纳米材料的出现有望突破上述瓶颈。金属纳米颗粒能够释放金属离子破坏细菌生物膜结构实现广谱杀菌[2];纳米壳聚糖有着良好的生物相容性和抗菌性能[3];纳米级的氢氧化钙弥补了传统氢氧化钙的缺点[4];纳米抗菌颗粒还能作为辅助剂添加至封闭剂和树脂中增加其抗菌性能;尤其是新型纳米递送系统的出现,不仅能搭载两种及以上抗菌分子,还能具有智能控释等功能。新材料的出现为防治牙髓根尖周疾病带来了新思路,本文就纳米抗菌材料在根管治疗方面的研究进展作一综述。

1　纳米抗菌材料

1.1　金属纳米颗粒

金属纳米颗粒是纳米材料中重要的组成部分,凭借其独特的理化性质广泛应用于能源、催化、医药等领域。金属纳米颗粒的制备方法多种多样,可将金属材料蒸发喷溅到基底上通过物理方法获得纳米颗粒,化学方法则可利用还原剂将金属离子还原为纳米颗粒[5],而新型的光化学法和生物合成法能够减少环境的负担[6]。具有抗菌作用的金属纳米颗粒主要有:银纳米颗粒、金纳米颗粒、铜纳米颗粒、锌纳米颗粒及钯纳米颗粒等。其中银纳米颗粒、氧化锌纳米颗粒是目前应对以粪肠球菌为代表的根管微生物感染挑战的重要手段。

1.1.1　银纳米颗粒　银纳米颗粒(silver nanoparticles,AgNPs)的粒径通常小于100 nm,具有比表面积高、表面活性强的物理特性[6]以及良好的催化性能,能高效催化氧化还原反应[7],因而银纳米颗粒的合成以化学还原法居多。其抗菌机制主要通过释放Ag^+破坏细胞膜、使DNA变性及产生活性氧等,这种多靶点作用可降低细菌耐药[8]。针对顽固性根尖周炎相关菌——粪肠球菌[9],AgNPs被证明对粪肠球菌及其耐药菌株有良好的抗菌作用[10-11]。30 nm粒径、100 ppm浓度的AgNPs联合氢氧化钙使用可显著减少根管内细菌的数量[12]。AgNPs可同氢氧化钙联合使用,既降低了AgNPs对粪肠球菌的最小抑菌浓度,也保留了氢氧化钙促进牙本质再矿化的优势[13]。凝胶形式的AgNPs与氢氧化钙共同应用时,能延长抗菌分子与细菌细胞壁的接触时间从而实现长效抗菌[14]。当AgNPs糊剂应用于根管封药时,其抗菌效果与氢氧化钙相当,且24 h内缓解根管治疗的术后不适感[15]。但AgNPs作为冲洗剂时,5 min内抗生物膜活性弱于2%氯己定,需15 min达同等效果[16],其抗菌效率也不如次氯酸钠[17]。AgNPs与其他根管材料联合可增强抗菌性:改良三氧化矿物凝聚体(mineral trioxide aggregate, MTA)后,其抗粪肠球菌能力、生物相容性及成骨性能均提升,促进成骨相关基因表达[18]。在AgNPs改性牙胶尖可长效缓释Ag^+抗菌[19]。

安全性方面,AgNPs细胞毒性受粒径、形貌、浓度及作用时间等影响:10 nm球形AgNPs在≥5 μg/mL或14 μg/mL(粒径<10 nm)时对人间充质干细胞

产生毒性[20-21]。相同浓度下球形AgNPs的抗菌活性优于圆盘形和三角板形，这3种形状对成纤维细胞的生长均无显著影响[22]。AgNPs的细胞毒性可能为暂时性，研究指出低浓度（0.01%）AgNPs在3 d和7 d对牙髓干细胞表现出明显毒性，而高浓度（质量百分比为0.015%和0.02%）AgNPs则因聚集效应反而导致毒性较低，但7 d后细胞活力均逐步恢复[23]。

AgNPs作为糊剂或凝胶剂型用于根管封药时显著减少粪肠球菌感染。虽无法作为根管冲洗剂，但将其添加至牙胶尖等材料中可赋予其长期抗菌性能。然而现有研究都集中在体外实验，缺乏长期临床试验的疗效评价，加上目前纳米材料缺乏统一合成方法，使得每一批次制备出的纳米颗粒在大小、形貌等方面的不同而直接影响其抗菌性和细胞毒性。

1.1.2　氧化锌纳米颗粒　氧化锌纳米颗粒（zinc oxide nanoparticles，ZnO NPs）粒径为20～60 nm，电镜下呈球形或六边形，六方纤锌矿的空间结构使其具有高比表面积[24]。常温下化学性质稳定，酸/碱环境下可释放锌离子[25]，并能在紫外光下产生活性氧[26]。通过Zn^{2+}释放干扰细菌代谢（抑制氨基酸运输及酶系统）、活性氧生成、及物理破坏等机制发挥抗菌作用[27-28]。且具有低成本、绿色合成的优势。一种从石榴叶中提取并合成的ZnO NPs对粪肠球菌和白色念珠菌的最小抑菌浓度分别为40 μg/mL和30 μg/mL，且具备较小的细胞毒性[29]。将ZnO NPs以质量分数为20%掺入氢氧化钙中可显著增强抗粪肠球菌效果，破坏细菌膜完整性[30]。作为冲洗剂时，0.1%浓度可提高牙本质显微硬度和根管抗断裂性，优于次氯酸钠[31-32]。以25%质量百分比替代密封剂传统氧化锌成分可改善材料理化性能[33]。

ZnO NPs的细胞毒性与浓度及暴露时间密切相关。24 h内≤40 μg/mL对牙龈成纤维细胞无显著毒性，但48 h后所有浓度（1～100 μg/mL）ZnO NPs均致细胞存活率显著下降。而包埋于聚乳酸-羟基乙酸共聚物基质可降低其毒性，尤其当ZnO浓度低于80 μg/mL时[34-35]。

因此ZnO NPs有望作为新型根管冲洗剂应用于未来临床，或添加至密封剂等材料中以增强抗菌性能。其长时间暴露对细胞活性的影响，限制了其在根管封药中的应用，需对其进行包封或改性以增加其安全性。

1.2　壳聚糖纳米颗粒

壳聚糖是由甲壳素脱乙酰化制得的天然生物材料[36]。天然壳聚糖在水中溶解度有限，表面活性较低[37]，通过离子或共价交联法可将其纳米化形成纳米壳聚糖（chitosan nanoparticles，CS-NPs），可改善溶解性和分散性、增加机械强度和稳定性[38-39]。CS-NPs的粒径因制备方法和条件不同通常在几十纳米到几百纳米之间，形状为球形[40]，能够在生物体内逐渐分解为无害的小分子，最终代谢为二氧化碳和水排出体外[41]。CS-NPs的氨基在酸性环境中质子化，通过静电吸附破坏细菌细胞膜通透性[42-43]。低分子量的CS-NPs还能够穿过细胞壁与胞内DNA结合、螯合代谢相关的金属离子、与核糖体结合影响蛋白质合成，从而抑制细菌繁殖[44]。

在根管治疗中，CS-NPs作为冲洗液和封药材料潜力显著。临床上常用EDTA清洗根管，然而EDTA缺乏抗菌特性，长期使用也有降低牙本质硬度的风险[45]，研究发现质量百分比17% CS-NPs与0.2% EDTA相比，去污效果相当且牙本质显微硬度更高、表面粗糙度更低[46]。CS-NPs悬浮液处理牙本质可显著降低细菌活性，去污效果优于次氯酸钠[47]，60 min内可完全清除临床上分离出来的4种粪肠球菌[48]。4 mg/mL浓度下抗粪肠球菌生物膜效果优于氢氧化钙，抗白色念珠菌效果与之相当[49]。通过将CS-NP溶于丙二醇制作成糊剂用于根管封药，可显著抑制根管内白色念珠菌和粪肠球菌组成的双菌种生物膜中的活菌数量[50-51]。与氯己定或三联抗生素联用增强生物膜清除能力[52-53]。此外，CS-NPs应用4周后牙本质抗折性及显微硬度均优于氢氧化钙组[3,54]。

作为食品药品监督管理局（Food and Drug Administration，FDA）认可的高生物相容性纳米材料，CS-NPs对人牙龈成纤维细胞毒性低，质量百分比10%～30%浓度添加至环氧树脂封闭剂可提升生物安全性[55-56]。体内动物实验也证明CS-NPs具有良好的生物安全性和血液相容性[57]。因此CS-NPs有作为根管冲洗液的潜力，同时也在根管封药方面有较大应用前景。

综上，CS-NPs对粪肠球菌和白色念珠菌具有良好的抗菌性，去污效果与乙二胺四乙酸（ethylene diamine tetraacetic acid，EDTA）相当但更安全；长期使用可维持牙本质硬度和抗折性，兼具冲洗和封药的潜力。天然壳聚糖水溶性差的问题可通

过纳米技术对其进行改性、包封等方法解决，但纳米壳聚糖的长期抗菌效果及临床转化方面的数据仍需进一步验证。

1.3　氢氧化钙纳米颗粒

通过机械球磨法、化学沉淀法等技术可制备出粒径为50～200 nm的氢氧化钙纳米颗粒[calcium hydroxide nanoparticles，Ca(OH)$_2$ NPs][58]。纳米尺寸的高比表面积使其在水中的溶解度和反应活性提升，进而增加抗菌性和生物活性[59]。Ca(OH)$_2$ NPs的抗菌机制主要为两方面：①释放OH^-提升环境pH值；②纳米化状态下具有较高表面能，使其与细菌细胞膜相互作用，破坏细胞膜的完整性[60-61]。

Ca(OH)$_2$ NPs对感染根管内的微生物有较强的杀菌能力。体外实验表明，Ca(OH)$_2$ NPs对根管混合感染中的主要病原体粪肠球菌、白色念珠菌、牙龈卟啉单胞菌等具有高效抑制作用[62-63]。通过乳酸-羟基乙酸共聚物负载技术制备的Ca(OH)$_2$ NPs可实现长效缓释功能：30 d钙离子释放量显著高于传统氢氧化钙制剂[64]，这种持续释放特性能够有效抑制根管内的病原微生物[65]。值得注意的是，其抗菌机制不仅限于直接杀菌，还可通过抑制破骨细胞分化间接调控感染微环境[66]。Ca(OH)$_2$ NPs对牙本质小管有良好的渗透作用。显微分析显示其在根管不同部位对牙本质小管的渗透深度为：1 526.52 μm（冠状部），1 178.66 μm（中部），1 214.027 μm（根尖部）[3]，这种渗透能力利于药物抵达根管内较深的感染区域。为验证其在根管内的抗菌性，研究人员构建了粪肠球菌生物膜感染的离体根管模型：经Ca(OH)$_2$ NPs处理1周后，共聚焦激光扫描显微镜显示生物膜中死菌比例显著升高，扫描电镜下生物膜得到明显破坏，这证实了Ca(OH)$_2$ NPs清除牙本质小管内生物膜的能力，并且优于传统氢氧化钙[67]。传统Ca(OH)$_2$对牙本质的组成和根折抗性有显著影响，暴露于Ca(OH)$_2$的时间越长，牙本质的抗断裂性显著降低，长期使用Ca(OH)$_2$作为根管内封药可能会导致牙本质的矿物质与基质比例降低，从而影响其显微硬度[68]，而用Ca(OH)$_2$ NPs封药4周后，牙本质硬度与对照组无统计学差异[69]，这一特性对维持根管治疗后牙体力学性能至关重要。同时实验证实了Ca(OH)$_2$ NPs的细胞毒性呈现浓度依赖性，对小鼠或人成纤维细胞有较低的细胞毒性[70-71]，目前尚未有该纳米颗粒对口腔内细胞毒性的相关研究报道。当前研究表明，Ca(OH)$_2$ NPs在牙本质小管渗透、细菌生物膜清除及对牙本质硬度影响方面具有显著优势，但其生物安全性需要大量实验来进一步验证。

1.4　季铵聚乙烯亚胺纳米颗粒

季铵聚乙烯亚胺（quaternary ammonium polyethyleneimine，QPEI）是一种纳米聚合物，具有吸附性和成膜性[72]。聚乙烯亚胺在水中具有稳定的化学性质，不易水解或降解。然而其中的氨基仍具有高反应性，可以很容易被修饰以获得季铵聚乙烯亚胺衍生物[73-74]。季铵化之后的聚乙烯亚胺对革兰氏阳性菌和革兰氏阴性菌表现出良好的抗菌活性。分子中带正电的铵基首先与带负电的细菌细胞壁结合，通过置换二价阳离子破坏电化学平衡使内容物流出，致细菌死亡[75-77]。目前相关研究集中在将其添加至复合树脂和根管封闭材料中以增强材料抗菌性方面。在离体牙模型中，研究者将1% QPEI纳米颗粒（质量比）掺入双组分环氧树脂基根管密封剂（AH Plus），评估其对牙本质小管内粪肠球菌的抗菌效果。7 d后含QPEI组牙本质小管内活菌比例较对照组显著降低（$P<0.01$）。这表明，1% QPEI纳米颗粒的掺入可提升密封剂的抗菌能力[78]。其关键优势在于，QPEI的引入未显著改变封闭剂的流动性、固化时间等关键理化性质，实现了抗菌性能与材料功能的兼容[79]。且含QPEI的树脂对细胞活力影响较小；体内实验中，植入含2% QPEI复合树脂的大鼠未出现局部炎症反应[80]，在人体试验中同样被证明可安全口服[81]。因此QPEI的核心优势在于通过纳米改性赋予牙科材料长效抗菌性，且不影响材料的机械性能与生物安全性。这为开发兼具多功能的下一代根管治疗材料提供了重要思路。

2　纳米递送系统

将纳米级颗粒作为载体装载药物或其他生物活性物质，凭借其小尺寸和高比表面积可实现药物的高效负载、靶向递送和缓释目的[82]。将抗菌剂或光敏剂封装至纳米颗粒中可增强抗菌效果，通过光激活纳米颗粒释放抗菌药物[83-84]。介孔硅酸钙和介孔二氧化硅因其独特的物理化学性质和生物相容性，在口腔医学领域展现出广阔的应用前景。

2.1　介孔硅酸钙

介孔硅酸钙纳米颗粒（mesoporous calcium-silicate nanoparticles，MCSNs）通常呈球形和类球形

结构，粒径范围为100～250 nm，具有高度有序的2～10 nm的介孔结构，有100～300 m^2/g的高比表面积和0.1～1.0 cm^3/g良好的孔隙容积[85-86]。这种结构使其能够高效搭载药物分子。钙、硅、氧是组成MCSNs的主要元素，分子中富含Si-OH基团，赋予材料良好的化学稳定性[87]。MCSNs表面带有正电荷，能够与带负电的细菌结合，释放孔道内抗菌分子从而达到抑制细菌生长的目的[88]。

通过吸附法合成的银修饰介孔二氧化硅纳米颗粒经超声激活后，可聚集于根管壁并浸润至牙本质小管，显著抑制粪肠球菌的黏附生物膜形成[89]。为进一步优化抗菌性能与生物相容性，将锌引入其中构建了银/锌共修饰的MCSNs（Ag/Zn-MCSNs）。锌元素的引入不仅增强抗生物膜活性，还能通过调节Ag/Zn比例平衡材料的抗菌活性和细胞毒性，同时维持牙本质弯曲强度及弹性模量，相较于氢氧化钙在牙本质硬度保护方面具有显著优势[90-91]。当MCSN搭载氯己定（2%）时能够在体外持续释放氯己定，具有低毒性的同时封闭牙本质小管，避免进一步的牙髓感染[92]。非离子去污剂Triton X-100可以与细胞膜的脂质体结合，从而提高膜的渗透性，将其同低剂量银离子负载至MCSN上可使粪肠球菌生物膜完全失活，且增加牙本质硬度促进再矿化[93]。MCSN纳米颗粒的细胞毒性与浓度密切相关。在12.5～100 μg/mL的浓度范围内，MCSN对牙周膜细胞无显著毒性，而当浓度超过40 μg/mL时，MCSN降低了骨髓间充质干细胞的活性[94]。

2.2　介孔二氧化硅

介孔二氧化硅纳米颗粒（mesoporous silica nanoparticles，MSNs）是一种具有2～50 nm规则孔道结构的无机纳米颗粒，比表面积可达1 000 m^2/g，低密度和多孔结构使其在溶液中具有良好的分散性，能够均匀分布于不同的介质中[95-96]。表面含有的大量硅羟基（Si-OH），可以进行化学修饰，引入不同的官能团（如氨基、羧基等），从而赋予材料不同的功能[97]。

芦丁和姜黄素是具有抗菌作用的天然成分，水溶度低和生物利用度差限制了它们的实际应用。借助MSNs中孔道将二者负载其中可显著提高抗菌效果，对粪肠球菌有良好的抑制作用[98]。MSNs不仅能够保护天然抗菌分子，还能与声敏剂原卟啉耦联，负载铁离子形成新型抗菌剂，不仅展现出优于传统次氯酸钠的抗生物膜能力，同时具有更佳的生物相容性[99]。MSNs也为多药物联合应用提供了理想载体。将溶菌酶与万古霉素共载于MSNs后，两者表现出显著协同效应，其对粪肠球菌的最小抑菌浓度较单一药物显著降低[100]。氯己定和银纳米颗粒共载的MSNs也显示出良好的抗感染根管内细菌生物膜的能力[101]。并且功能化MSNs中的二硫键桥有机硅部分可以以细胞内氧化还原响应方式进行生物降解[102]，具有良好的可降解性和生物安全性[103]。

纳米递送系统在根管治疗中具有精准控释、高效抗菌及低全身毒性的优势[104]。高比表面积和丰富的孔道能够搭载大量不同种类的药物分子，不仅能联合发挥药物的功能，还能解决天然抗菌分子易在体内降解的问题；通过对表面进行功能化修饰改造，能使其根据作用部位独特的微环境如pH值、温度、氧化应激反应等作出响应，从而实现智能释放的目的。虽然目前纳米递送系统在实验室取得较好的实验结果，但其长期安全性数据不足、稳定性差（易降解）、及成本高昂的问题有待解决。

3　结　语

本文综述了金属纳米颗粒、壳聚糖纳米颗粒、氢氧化钙纳米颗粒、季铵聚乙烯亚胺纳米颗粒、纳米递送系统在根管治疗方面的研究进展。相关材料的优缺点详见表1。纳米微小的体积、高效的抗菌性与良好的生物安全性使得纳米抗菌材料在根管治疗领域展现出较大应用前景。目前纳米抗菌材料在根管治疗中主要采用凝胶、悬浮液或糊剂等实验剂型，或添加至现有材料中（如封闭剂、树脂）增加抗菌性能。现有研究仍处于实验室阶段，纳米抗菌材料临床转化仍面临多重挑战：①高比表面积易引发颗粒聚集，需通过表面修饰优化稳定性；②批次间粒径分布差异难以精准调控（如10～30 nm颗粒混杂、表面修饰密度不一等）；③缺乏统一的全球质量标准与表征规范，制约数据可比性。未来研究应聚焦于多功能纳米材料的开发，并完善现有材料的长期生物安全性研究。为纳米技术向临床转化奠定坚实的基础。

【Author contributions】 Wang YY conceptualized and wrote the article. Qin L, Jia YM, Du XS, Liu F collected the references, revised the article. Wang SP conceptualized and revised the article. All authors read and approved the final manuscript as submitted.

表1　纳米抗菌材料在根管治疗应用中的优缺点

Table 1　Advantages and disadvantages of antimicrobial nanomaterials in endodontic applications

Material	Advantages	Disadvantages
AgNPs	① Broad-spectrum antibacterial activity with multi-target effects, reducing resistance risk; ② Can be combined with calcium hydroxide; ③ Applicable in root canal medication or as an antibacterial enhancer in other materials.	① Cytotoxicity depends on concentration and particle size; ② Predominantly studied in vitro, lacking clinical data; ③ Poor batch stability.
ZnO NPs	① Low cost, eco-friendly synthesis, and light-responsive release; ② Enhances dentin microhardness and fracture resistance; ③ Can be used as a root canal irrigant or additive in sealers.	① Prolonged exposure reduces cell viability, requiring surface modification; ② Antibacterial efficacy limited by concentration.
CS-NPs	① High biocompatibility; ② Synergistic effects with antibiotics; ③ Maintains dentin hardness and potential for irrigation/sealing.	① Poor water solubility of natural chitosan requires nano-modification; ② Insufficient long-term antibacterial data and clinical validation.
$Ca(OH)_2$ NPs	① High permeability and sustained release of OH^- ions; ② Protects dentin hardness, superior to traditional formulations; ③ Applicable in root canal medication.	① Biosafety requires further validation; ② Lack of studies on cytotoxicity to oral cells.
QPEI	① Imparts long-term antibacterial properties without affecting physicochemical performance; ② Low cytotoxicity with validated in vitro/in vivo safety; ③ Suitable for incorporation into sealers to enhance antibacterial activity.	① Research focuses on sealers and resin modification; ② lacks standalone studies for root canal applications.
MCSNs/MSNs	① High drug-loading capacity and controlled release; ② Enables synergistic antibacterial drug combinations; ③ Strong surface modifiability; ④ Suitable for root canal medication.	① Significant cytotoxicity at high concentrations and poor long-term stability; ② High production cost and lack of standardized quality control.

AgNPs: silver nanoparticles; ZnO NPs: zinc oxide nanoparticles; CS-NPs: chitosan nanoparticles; $Ca(OH)_2$ NPs: calcium hydroxide nanoparticles; QPEI: quaternary ammonium polyethyleneimine; MCSNs: mesoporous calcium-silicate nanoparticles; MSNs: mesoporous silica nanoparticles

参考文献

[1] Feng Y, Sun Q, Liu P, et al. Antibacterial property and mechanisms of Au@Ag core-shell nanoparticles with near-infrared absorption against *E. faecalis* infection of dentin[J]. Int J Nanomedicine, 2024, 19: 6981-6997. doi: 10.2147/IJN.S468649.

[2] Piri-Gharaghie T, Beiranvand S, Riahi A, et al. Fabrication and characterization of thymol-loaded chitosan nanogels: improved antibacterial and anti-biofilm activities with negligible cytotoxicity [J]. Chem Biodivers, 2022, 19(3): e202100426. doi: 10.1002/cbdv.202100426.

[3] Prashanth BR, Revankar B, Karale R, et al. Comparative assessment of nanosized intracanal medicaments on penetration and fracture resistance of root dentin - an *in vitro* study[J]. J Conserv Dent Endod, 2024, 27(1): 17-23. doi: 10.4103/JCDE.JCDE_138_23.

[4] Prahasti AE, Yuanita T, Rahayu RP. Novel combination of nanostructured calcium hydroxide and natural materials: formulation and characterization[J]. Dent Med Probl, 2024, 61(5): 721-728. doi: 10.17219/dmp/161988.

[5] Luty-Błocho M, Cyndrowska J, Rutkowski B, et al. Synthesis of gold clusters and nanoparticles using cinnamon extract-a mechanism and kinetics study[J]. Molecules, 2024, 29(7): 1426. doi: 10.3390/molecules29071426.

[6] Kang J, Dietz MJ, Hughes K, et al. Silver nanoparticles present high intracellular and extracellular killing against *Staphylococcus aureus*[J]. J Antimicrob Chemother, 2019, 74(6): 1578-1585. doi: 10.1093/jac/dkz053.

[7] 刘雪霆, 吴晶晶, 顾星, 等. 纳米银颗粒负载UiO-66复合材料的合成及其催化性能[J]. 化工新型材料, 2022, 50(1): 121-125. doi: 10.19817/j.cnki.issn1006-3536.2022.01.025.
Liu XT, Wu JJ, Gu X, et al. Synthesis and catalytic performance of nano silver particle supported UiO-66 composite[J]. New Chem Mater, 2022, 50(1): 121-125. doi: 10.19817/j.cnki.issn1006-3536.2022.01.025.

[8] Sorinolu AJ, Godakhindi V, Siano P, et al. Influence of silver ion release on the inactivation of antibiotic resistant bacteria using light-activated silver nanoparticles[J]. Mater Adv, 2022, 3(24): 9090-9102. doi: 10.1039/d2ma00711h.

[9] Barbosa-Ribeiro M, Arruda-Vasconcelos R, Louzada LM, et al. Microbiological analysis of endodontically treated teeth with apical periodontitis before and after endodontic retreatment[J]. Clin Oral Investig, 2021, 25(4): 2017-2027. doi: 10.1007/s00784-020-03510-2.

[10] Afkhami F, Pourhashemi SJ, Sadegh M, et al. Antibiofilm efficacy of silver nanoparticles as a vehicle for calcium hydroxide medica-

ment against *Enterococcus faecalis*[J]. J Dent, 2015, 43(12): 1573-1579. doi: 10.1016/j.jdent.2015.08.012.

[11] Ramzan M, Karobari MI, Heboyan A, et al. Synthesis of silver nanoparticles from extracts of wild ginger (zingiber zerumbet) with antibacterial activity against selective multidrug resistant oral bacteria[J]. Molecules, 2022, 27(6): 2007. doi: 10.3390/molecules27062007.

[12] Afkhami F, Rostami G, Batebi S, et al. Residual antibacterial effects of a mixture of silver nanoparticles/calcium hydroxide and other root canal medicaments against *Enterococcus faecalis*[J]. J Dent Sci, 2022, 17(3): 1260-1265. doi: 10.1016/j.jds.2021.11.013.

[13] Ghahramani Y, Yaghoobi F, Motamedi R, et al. Effect of endodontic irrigants and medicaments mixed with silver nanoparticles against biofilm formation of *Enterococcus faecalis*[J]. Iran Endod J, 2018, 13(4): 559-564. doi: 10.22037/iej.v13i4.21843.

[14] Fahim MM, Saber SEM, Elkhatib WF, et al. The antibacterial effect and the incidence of post-operative pain after the application of nano-based intracanal medications during endodontic retreatment: a randomized controlled clinical trial[J]. Clin Oral Investig, 2022, 26(2): 2155-2163. doi: 10.1007/s00784-021-04196-w.

[15] Abdou SA, Mohamed AI. Evaluation of antibacterial effect of silver nanoparticles paste with and without curcumin as intracanal medication[J]. Bull Natl Res Cent, 2022, 46(1): 36. doi: 10.1186/s42269-022-00723-1.

[16] Rodrigues CT, de Andrade FB, de Vasconcelos LRSM, et al. Antibacterial properties of silver nanoparticles as a root canal irrigant against *Enterococcus faecalis* biofilm and infected dentinal tubules [J]. Int Endod J, 2018, 51(8): 901-911. doi: 10.1111/iej.12904.

[17] Oncu A, Celikten B, Aydın B, et al. Antibacterial efficacy of silver nanoparticles, sodium hypochlorite, chlorhexidine, and hypochlorous acid on dentinal surfaces infected with *Enterococcus faecalis* [J]. Microsc Res Tech, 2024, 87(9): 2094-2102. doi: 10.1002/jemt.24590.

[18] Lee MY, Yoon HW, Kim KM, et al. Antibacterial efficacy and osteogenic potential of mineral trioxide aggregate-based retrograde filling material incorporated with silver nanoparticle and calcium fluoride[J]. J Dent Sci, 2024, 19(3): 1783-1791. doi: 10.1016/j.jds.2023.10.001.

[19] Monisha K, Shilpa SA, Hikku GS. *In-situ* nano-Ag coated gutta percha cones to counteract internal endodontic failures through bacterial infections[J]. Mater Chem Phys, 2023, 301: 127532. doi: 10.1016/j.matchemphys.2023.127532.

[20] Greulich C, Kittler S, Epple M, et al. Studies on the biocompatibility and the interaction of silver nanoparticles with human mesenchymal stem cells (hMSCs)[J]. Langenbecks Arch Surg, 2009, 394 (3): 495-502. doi: 10.1007/s00423-009-0472-1.

[21] Ptasiewicz M, Chałas R, Idaszek J, et al. *In vitro* effects of silver nanoparticles on pathogenic bacteria and on metabolic activity and viability of human mesenchymal stem cells[J]. Arch Immunol Ther Exp(Warsz), 2024, 72(1). doi: 10.2478/aite-2024-0007.

[22] Cheon JY, Kim SJ, Rhee YH, et al. Shape-dependent antimicrobial activities of silver nanoparticles[J]. Int J Nanomedicine, 2019, 14: 2773-2780. doi: 10.2147/IJN.S196472.

[23] Mahmoud A, Moussa S, El Backly R, et al. Investigating the residual effect of silver nanoparticles gel as an intra-canal medicament on dental pulp stromal cells[J]. BMC Oral Health, 2022, 22 (1): 545. doi: 10.1186/s12903-022-02542-2.

[24] Javidi M, Zarei M, Naghavi N, et al. Zinc oxide nano-particles as sealer in endodontics and its sealing ability[J]. Contemp Clin Dent, 2014, 5(1): 20-24. doi: 10.4103/0976-237X.128656.

[25] Park N, Kim KS, Lee S, et al. Enhanced stem cell-mediated therapeutic immune modulation with zinc oxide nanoparticles in liver regenerative therapy[J]. Biomaterials, 2025, 320: 123232. doi: 10.1016/j.biomaterials.2025.123232.

[26] Singh K, Neha, Kumar M, et al. ZnO NPs: photocatalytic potential, mechanistic insights, favorable parameters and challenges[J]. Mater Today Proc, 2023. doi: 10.1016/j.matpr.2023.03.002.

[27] Hussien NA, Khalil MAEF, Schagerl M, et al. Green synthesis of zinc oxide nanoparticles as a promising nanomedicine approach for anticancer, antibacterial, and anti-inflammatory therapies[J]. Int J Nanomedicine, 2025, 20: 4299-4317. doi: 10.2147/IJN.S507214.

[28] Qu B, Xiao Z, Luo Y. Sustainable nanotechnology for food preservation: synthesis, mechanisms, and applications of zinc oxide nanoparticles[J]. J Agric Food Res, 2025, 19: 101743. doi: 10.1016/j.jafr.2025.101743.

[29] Thejashwini PP, Chandrika R, Madhusudhan MC, et al. Psidium guajav-mediated zinc oxide nanoparticles as a multifunctional, microbicidal, antioxidant and antiproliferative agent against destructive pathogens[J]. Bioprocess Biosyst Eng, 2024, 47(9): 1571-1584. doi: 10.1007/s00449-024-03052-x.

[30] Nair N, James B, Devadathan A, et al. Comparative evaluation of antibiofilm efficacy of chitosan nanoparticle- and zinc oxide nanoparticle-incorporated calcium hydroxide-based sealer: an *in vitro* study[J]. Contemp Clin Dent, 2018, 9(3): 434-439. doi: 10.4103/ccd.ccd_225_18.

[31] Sahebi S, Mofidi H, Abbaszadegan A, et al. The effect of nano-based irrigants on the root canal dentin microhardness: an *ex-vivo* study[J]. BMC Oral Health, 2023, 23(1): 581. doi: 10.1186/s12903-023-03298-z.

[32] Jowkar Z, Hamidi SA, Shafiei F, et al. The effect of silver, zinc oxide, and titanium dioxide nanoparticles used as final irrigation solutions on the fracture resistance of root-filled teeth[J]. Clin Cosmet Investig Dent, 2020, 12: 141-148. doi: 10.2147/CCIDE.S253251.

[33] Versiani MA, Abi Rached-Junior FJ, Kishen A, et al. Zinc oxide nanoparticles enhance physicochemical characteristics of grossman sealer[J]. J Endod, 2016, 42(12): 1804-1810. doi: 10.1016/j.joen.2016.08.023.

[34] Burmistrov DE, Simakin AV, Smirnova VV, et al. Bacteriostatic and cytotoxic properties of composite material based on ZnO nanoparticles in PLGA obtained by low temperature method[J]. Polymers(Basel), 2021, 14(1): 49. doi: 10.3390/polym14010049.

[35] Mozaffari A, Mirzapour SM, Rad MS, et al. Cytotoxicity of PLGA-zinc oxide nanocomposite on human gingival fibroblasts[J]. J Adv Periodontol Implant Dent, 2023, 15(1): 28-34. doi: 10.34172/

japid.2023.010.

[36] Lunawat AK, Mukherjee D, Shivgotra R, et al. Carboplatin co-loaded 5-fluorouracil nanoparticles conjugated with trastuzumab for targeted therapy in $HER2^{+}$ heterogeneity breast cancer[J]. AAPS PharmSciTech, 2025, 26(5): 114. doi: 10.1208/s12249-025-03107-6.

[37] Jiang Y, Fu C, Wu S, et al. Determination of the deacetylation degree of chitooligosaccharides[J]. Mar Drugs, 2017, 15(11): 332. doi: 10.3390/md15110332.

[38] Sun L, Chen Y, Zhou Y, et al. Preparation of 5-fluorouracil-loaded chitosan nanoparticles and study of the sustained release *in vitro* and *in vivo*[J]. Asian J Pharm Sci, 2017, 12(5): 418-423. doi: 10.1016/j.ajps.2017.04.002.

[39] Ahmad N, Khan MR, Palanisamy S, et al. Anticancer drug-loaded chitosan nanoparticles for *in vitro* release, promoting antibacterial and anticancer activities[J]. Polymers(Basel), 2023, 15(19): 3925. doi: 10.3390/polym15193925.

[40] El-Ganainy SM, Soliman AM, Ismail AM, et al. Antiviral activity of chitosan nanoparticles and chitosan silver nanocomposites against alfalfa mosaic virus[J]. Polymers(Basel), 2023, 15(13): 2961. doi: 10.3390/polym15132961.

[41] Zhang X, Teng Z, Huang R, et al. Biodegradable starch/chitosan foam *via* microwave assisted preparation: morphology and performance properties[J]. Polymers(Basel), 2020, 12(11): 2612. doi: 10.3390/polym12112612.

[42] Saito H, Sakakibara Y, Sakata A, et al. Antibacterial activity of lysozyme-chitosan oligosaccharide conjugates (LYZOX) against *Pseudomonas aeruginosa*, *Acinetobacter baumannii* and Methicillin-resistant *Staphylococcus aureus*[J]. PLoS One, 2019, 14(5): e0217504. doi: 10.1371/journal.pone.0217504.

[43] Xing Y, Wang X, Guo X, et al. Comparison of antimicrobial activity of chitosan nanoparticles against bacteria and fungi[J]. Coatings, 2021, 11(7): 769. doi: 10.3390/coatings11070769.

[44] Mirbagheri VS, Alishahi A, Ahmadian G, et al. Toward understanding the antibacterial mechanism of chitosan: experimental approach and in silico analysis[J]. Food Hydrocoll, 2024, 147: 109382. doi: 10.1016/j.foodhyd.2023.109382.

[45] El-Banna A, Elmesellawy MY, Elsayed MA. Flexural strength and microhardness of human radicular dentin sticks after conditioning with different endodontic chelating agents[J]. J Conserv Dent, 2023, 26(3): 344-348. doi: 10.4103/jcd.jcd_173_23.

[46] Ratih DN, Enggardipta RA, Kartikaningtyas AT. The effect of chitosan nanoparticle as a final irrigation solution on the smear layer removal, micro-hardness and surface roughness of root canal dentin[J]. Open Dent J, 2020, 14(1): 19-26. doi: 10.2174/1874210602014010019.

[47] Del Carpio-Perochena A, Bramante CM, Duarte MA, et al. Chelating and antibacterial properties of chitosan nanoparticles on dentin [J]. Restor Dent Endod, 2015, 40(3): 195-201. doi: 10.5395/rde.2015.40.3.195.

[48] Supotngarmkul A, Panichuttra A, Ratisoontorn C, et al. Antibacterial property of chitosan against *E. faecalis* standard strain and clinical isolates[J]. Dent Mater J, 2020, 39(3): 456-463. doi: 10.4012/dmj.2018-343.

[49] Thienngern P, Panichuttra A, Ratisoontorn C, et al. Efficacy of chitosan paste as intracanal medication against *Enterococcus faecalis* and *Candida albicans* biofilm compared with calcium hydroxide in an *in vitro* root canal infection model[J]. BMC Oral Health, 2022, 22(1): 354. doi: 10.1186/s12903-022-02385-x.

[50] Srihawan O, Panichuttra A, Lertchirakarn V, et al. Efficacy of chitosan root canal medicament against cross-Kingdom dual-species biofilm of *Candida albicans* and *Enterococcus faecalis* in an *in vitro* root-canal model[J]. Odontology, 2025, 113(3): 959-964. doi: 10.1007/s10266-024-01024-x.

[51] Ugalmugale SR, Bohora AA, Patel PA, et al. Comparative evaluation of antibacterial efficacy of nitrofurantoin, chitosan, and calcium hydroxide in combination with propylene glycol as an intracanal medicament against endodontic pathogen - an *in vitro* study[J]. J Conserv Dent Endod, 2024, 27(8): 801-806. doi: 10.4103/JCDE.JCDE_172_24.

[52] Wassel M, Radwan M, Elghazawy R. Direct and residual antimicrobial effect of 2% chlorhexidine gel, double antibiotic paste and chitosan- chlorhexidine nanoparticles as intracanal medicaments against *Enterococcus faecalis* and *Candida albicans* in primary molars: an *in-vitro* study[J]. BMC Oral Health, 2023, 23(1): 296. doi: 10.1186/s12903-023-02862-x.

[53] Harshitha VS, Ranjini MA, Nadig RR. Antibacterial efficacy of nisin, calcium hydroxide, and triple antibiotic paste in combination with chitosan as an intracanal medicament against *Enterococcus faecalis* - an *in vitro* study[J]. J Conserv Dent, 2022, 25(5): 504-509. doi: 10.4103/jcd.jcd_125_22.

[54] Nasr M, Abdou A, Bassiouny DM, et al. Antibiofilm effect of Nano chitosan and calcium hydroxide intracanal medications and their effects on the microhardness and chemical structure of radicular dentine[J]. BMC Oral Health, 2025, 25(1): 103. doi: 10.1186/s12903-025-05462-z.

[55] Rajan B, Abdelmoneim D, Salem AS, et al. Nanoencapsulation, biocompatibility and antibiofilm properties of chitosan/nisin Z spheres[J]. Arch Oral Biol, 2025, 173: 106193. doi: 10.1016/j.archoralbio.2025.106193.

[56] Ratih DN, Mulyawati E, Santi RK, et al. Antibacterial and cytotoxicity of root canal sealer with the addition of chitosan nanoparticle at various concentrations[J]. Eur J Dent, 2023, 17(2): 398-402. doi: 10.1055/s-0042-1746415.

[57] Sonin D, Pochkaeva E, Zhuravskii S, et al. Biological safety and biodistribution of chitosan nanoparticles[J]. Nanomaterials(Basel), 2020, 10(4): 810. doi: 10.3390/nano10040810.

[58] Maguire CM, Rösslein M, Wick P, et al. Characterisation of particles in solution – a perspective on light scattering and comparative technologies[J]. Sci Technol Adv Mater, 2018, 19(1): 732-745. doi: 10.1080/14686996.2018.1517587.

[59] Taglieri G, Daniele V, Macera L, et al. Sustainable nanotechnologies for curative and preventive wood deacidification treatments: an eco-friendly and innovative approach[J]. Nanomaterials(Basel), 2020, 10(9): 1744. doi: 10.3390/nano10091744.

[60] Harish, Kumari S, Parihar J, et al. Synthesis, Characterization, and

antibacterial activity of calcium hydroxide nanoparticles against gram - positive and gram - negative bacteria [J]. ChemistrySelect, 2022, 7(37): e202203094. doi: 10.1002/slct.202203094.

[61] Veeraiyan M, Chandhar CY, Mastammanavar D, et al. Comparative evaluation of penetration of various nano-sized intra-canal medicaments: an *in vitro* confocal laser scanning microscopic study [J]. J Pharm Bioallied Sci. 2024; 16(Suppl 2): S1690-S1694. doi: 10.4103/jpbs.jpbs_942_23.

[62] Gautam N, Bohra SSK, Upadhyay R, et al. The evaluation of anti-osteoclastic activity of the novel calcium hydroxide biodegradable nanoparticles as an intracanal medicament[J]. J Pharm Bioallied Sci, 2024, 16(Suppl 4): S3815-S3817. doi: 10.4103/jpbs. jpbs_1288_24.

[63] Leelapornpisid W, Wanwatanakul P, Mahatnirunkul T. Efficacy of calcium hydroxide-loaded poly(lactic-co-glycolic acid) biodegradable nanoparticles as an intracanal medicament against endodontopathogenic microorganisms in a multi-species biofilm model[J]. Aust Endod J, 2024, 50(1): 89-96. doi: 10.1111/aej.12812.

[64] Chaiyosang P, Mahatnirunkul T, Leelapornpisid W. The effects of calcium hydroxide-loaded poly(lactic-co-glycolic acid) biodegradable nanoparticles in the *ex vivo* external inflammatory root resorption model[J]. J Contemp Dent Pract, 2023, 24(6): 351-356. doi: 10.5005/jp-journals-10024-3522.

[65] Elmsmari F, Delgado LM, Duran-Sindreu F, et al. Novel strategies enhancing endodontic disinfection: Antibacterial biodegradable calcium hydroxide nanoparticles in an *ex vivo* model[J]. Int J Pharm, 2023, 648: 123627. doi: 10.1016/j.ijpharm.2023.123627.

[66] Promta P, Chaiyosang P, Panya A, et al. The evaluation of anti-osteoclastic activity of the novel calcium hydroxide biodegradable nanoparticles as an intracanal medicament[J]. J Endod, 2024, 50(5): 667-673. doi: 10.1016/j.joen.2024.02.023.

[67] Louwakul P, Saelo A, Khemaleelakul S. Efficacy of calcium oxide and calcium hydroxide nanoparticles on the elimination of *Enterococcus faecalis* in human root dentin[J]. Clin Oral Investig, 2017, 21(3): 865-871. doi: 10.1007/s00784-016-1836-x.

[68] Al-Hiyasat AS, El-Farraj HS, Alebrahim MA. The effect of calcium hydroxide on dentine composition and root fracture resistance of human teeth: an *in vitro* study[J]. Eur J Oral Sci, 2021, 129(4): e12798. doi: 10.1111/eos.12798.

[69] Naseri M, Eftekhar L, Gholami F, et al. The effect of calcium hydroxide and nano-calcium hydroxide on microhardness and superficial chemical structure of root canal dentin: an *ex vivo* study[J]. J Endod, 2019, 45(9): 1148-1154. doi: 10.1016/j.joen.2019.06.002.

[70] Zhou F, Yang Y, Liu Y, et al. A calcium hydroxide/oleic acid/phospholipid nanoparticle induced cancer cell apoptosis by the combination of intracellular calcium overload and lactic acidosis elimination[J]. J Mater Chem B, 2023, 11(25): 5856-5869. doi: 10.1039/d3tb00227f.

[71] Mohamed HRH, Ibrahim EH, Shaheen SEE, et al. Calcium hydroxide nanoparticles induce cell death, genomic instability, oxidative stress and apoptotic gene dysregulation on human HepG2 cells [J]. Sci Rep, 2025, 15(1): 2993. doi: 10.1038/s41598-025-86401-4.

[72] Gao B, Zhang X, Sheng Y. Studies on preparing and corrosion inhibition behaviour of quaternized polyethyleneimine for low carbon steel in sulfuric acid[J]. Mater Chem Phys, 2008, 108(2/3): 375-381. doi: 10.1016/j.matchemphys.2007.10.033.

[73] Yu Y, Liu J, Liu Q, et al. Quaternized polyethyleneimine-polyacrylonitrile crosslinked membrane with excellent performance synthetized by homogeneous strategy for efficient uranium extraction from seawater[J]. Desalination, 2023, 565: 116828. doi: 10.1016/j.desal.2023.116828.

[74] Yudovin-Farber I, Golenser J, Beyth N, et al. Quaternary ammonium polyethyleneimine: antibacterial activity[J]. J Nanomater, 2010, 2010(1): 826343. doi: 10.1155/2010/826343.

[75] Gibney KA, Sovadinova I, Lopez AI, et al. Poly(ethylene imine)s as antimicrobial agents with selective activity[J]. Macromol Biosci, 2012, 12(9): 1279-1289. doi: 10.1002/mabi.201200052.

[76] Li Q, Wang L, Li Y, et al. Tannic acid coating modification of polypropylene providing pH-responsive antibacterial and anti-inflammatory properties applicable to ostomy patches[J]. Colloids Surf B Biointerfaces, 2025, 250: 114567. doi: 10.1016/j. colsurfb.2025.114567.

[77] Pietrokovski Y, Nisimov I, Kesler-Shvero D, et al. Antibacterial effect of composite resin foundation material incorporating quaternary ammonium polyethyleneimine nanoparticles[J]. J Prosthet Dent, 2016, 116(4): 603-609. doi: 10.1016/j. prosdent.2016.02.022.

[78] Abramovitz I, Wisblech D, Zaltsman N, et al. Intratubular antibacterial effect of polyethyleneimine nanoparticles: an *ex vivo* study in human teeth[J]. J Nanomater, 2015,. doi: 10.1155/2015/980529.

[79] Barros J, Silva MG, Rodrigues MA, et al. Antibacterial, physicochemical and mechanical properties of endodontic sealers containing quaternary ammonium polyethylenimine nanoparticles[J]. Int Endod J, 2014, 47(8): 725-734. doi: 10.1111/iej.12207.

[80] Yudovin-Farber I, Beyth N, Nyska A, et al. Surface characterization and biocompatibility of restorative resin containing nanoparticles[J]. Biomacromolecules, 2008, 9(11): 3044-3050. doi: 10.1021/bm8004897.

[81] Beyth N, Yudovin-Farber I, Perez-Davidi M, et al. Polyethyleneimine nanoparticles incorporated into resin composite cause cell death and trigger biofilm stress *in vivo*[J]. Proc Natl Acad Sci USA, 2010, 107(51): 22038-22043. doi: 10.1073/pnas.1010341107.

[82] Dănilă AI, Romînu M, Munteanu K, et al. Development of solid nanosystem for delivery of chlorhexidine with increased antimicrobial activity and decreased cytotoxicity: characterization and *in vitro* and in ovo toxicological screening[J]. Molecules, 2025, 30(1): 162. doi: 10.3390/molecules30010162.

[83] Jain G, Shukla P, Misra P, et al. Investigation of the potential of nanoparticles as a new drug delivery system for endodontic treatment: an *in vitro* study[J]. J Pharm Bioallied Sci, 2024, 16(Suppl 1): S921-S923. doi: 10.4103/jpbs.jpbs_1093_23.

[84] Pagonis TC, Chen J, Fontana CR, et al. Nanoparticle-based endodontic antimicrobial photodynamic therapy[J]. J Endod, 2010, 36(2): 322-328. doi: 10.1016/j.joen.2009.10.011.

[85] Chen CY, Shie MY, Lee AK, et al. 3D-printed ginsenoside Rb1-

loaded mesoporous calcium silicate/calcium sulfate scaffolds for inflammation inhibition and bone regeneration[J]. Biomedicines, 2021, 9(8): 907. doi: 10.3390/biomedicines9080907.

[86] Yeh CL, Bhorade R, Hsu TT, et al. Mechanical assessment and odontogenic behavior of a 3D-printed mesoporous calcium silicate/calcium sulfate/poly-ε-caprolactone composite scaffold[J]. J Formos Med Assoc, 2022, 121(2): 510-518. doi: 10.1016/j.jfma.2021.06.025.

[87] Huang KH, Chen CY, Chang CY, et al. The synergistic effects of quercetin-containing 3D-printed mesoporous calcium silicate/calcium sulfate/poly-ε-caprolactone scaffolds for the promotion of osteogenesis in mesenchymal stem cells[J]. J Formos Med Assoc, 2021, 120(8): 1627-1634. doi: 10.1016/j.jfma.2021.01.024.

[88] Wong KW, Li YJ, Yang HC, et al. Antimicrobial properties of bimetallic-containing mesoporous bioglass against *Enterococcus faecalis*[J]. J Dent Sci, 2025, 20(1): 510-521. doi: 10.1016/j.jds.2024.04.029.

[89] Fan W, Wu D, Tay FR, et al. Effects of adsorbed and templated nanosilver in mesoporous calcium-silicate nanoparticles on inhibition of bacteria colonization of dentin[J]. Int J Nanomedicine, 2014, 9: 5217-5230. doi: 10.2147/IJN.S73144.

[90] Leng D, Li Y, Zhu J, et al. The antibiofilm activity and mechanism of nanosilver- and nanozinc-incorporated mesoporous calcium-silicate nanoparticles[J]. Int J Nanomedicine, 2020, 15: 3921-3936. doi: 10.2147/IJN.S244686.

[91] Zhu J, Liang R, Sun C, et al. Effects of nanosilver and nanozinc incorporated mesoporous calcium-silicate nanoparticles on the mechanical properties of dentin[J]. PLoS One, 2017, 12(8): e0182583. doi: 10.1371/journal.pone.0182583.

[92] Gao Y, Huang P, Chen R, et al. Mesoporous calcium silicate nanoparticles for superficial dental tissue reconstruction, *in vitro* and *in vivo*[J]. RSC Adv, 2021, 11(40): 24681-24693. doi: 10.1039/d1ra02114a.

[93] Duan M, Fan W, Fan B. Mesoporous calcium-silicate nanoparticles loaded with low-dose triton-100+Ag^+ to achieve both enhanced antibacterial properties and low cytotoxicity for dentin disinfection of human teeth[J]. Pharmaceutics, 2021, 13(9): 1518. doi: 10.3390/pharmaceutics13091518.

[94] Zhao X, Wang Y, Zhu T, et al. Mesoporous calcium-silicate nanoparticles loaded with Prussian blue promotes *Enterococcus faecalis* ferroptosis-like death by regulating bacterial redox pathway ROS/GSH[J]. Int J Nanomedicine, 2022, 17: 5187-5205. doi: 10.2147/IJN.S382928.

[95] Liu X, Hu H, Ma J, et al. Mineralized cellulose nanofibers reinforced bioactive hydrogel remodels the osteogenic and angiogenic microenvironment for enhancing bone regeneration[J]. Carbohydr Polym, 2025, 357: 123480. doi: 10.1016/j.carbpol.2025.123480.

[96] Juneja R, Vadarevu H, Halman J, et al. Combination of nucleic acid and mesoporous silica nanoparticles: optimization and therapeutic performance *in vitro*[J]. ACS Appl Mater Interfaces, 2020, 12(35): 38873-38886. doi: 10.1021/acsami.0c07106.

[97] Eljack S, David S, Faggad A, et al. Nanoparticles design considerations to co-deliver nucleic acids and anti-cancer drugs for chemoresistance reversal[J]. Int J Pharm X, 2022, 4: 100126. doi: 10.1016/j.ijpx.2022.100126.

[98] Brezhnev A, Tang FK, Kwan CS, et al. One-pot preparation of cetylpyridinium chloride-containing nanoparticles for biofilm eradication[J]. ACS Appl Bio Mater, 2023, 6(3): 1221-1230. doi: 10.1021/acsabm.2c01080.

[99] Guo J, Xu Y, Liu M, et al. An MSN-based synergistic nanoplatform for root canal biofilm eradication *via* fenton-enhanced sonodynamic therapy[J]. J Mater Chem B, 2021, 9(37): 7686-7697. doi: 10.1039/d1tb01031j.

[100] Namdar N, Nayeri Fasaei B, Shariati P, et al. Mesoporous silica nanoparticles co-loaded with lysozyme and vancomycin for synergistic antimicrobial action[J]. Sci Rep, 2024, 14(1): 29242. doi: 10.1038/s41598-024-78922-1.

[101] Wang Y, Fang L, Wang P, et al. Antibacterial effects of silica nanoparticles loading nano-silver and chlorhexidine in root canals infected by *Enterococcus faecalis*[J]. J Endod, 2025, 51(1): 54-63. doi: 10.1016/j.joen.2024.11.004.

[102] Du X, Kleitz F, Li X, et al. Disulfide-bridged organosilica frameworks: designed, synthesis, redox-triggered biodegradation, and nanobiomedical applications[J]. Adv Funct Mater, 2018, 28(26): 1707325. doi: 10.1002/adfm.201707325.

[103] Wang S, Fang L, Zhou H, et al. Silica nanoparticles containing nano-silver and chlorhexidine respond to pH to suppress biofilm acids and modulate biofilms toward a non-cariogenic composition [J]. Dent Mater, 2024, 40(2): 179-189. doi: 10.1016/j.dental.2023.11.006.

[104] 张新坚, 张斌. 纳米粒子递药系统在牙周炎局部药物治疗中应用的研究进展[J]. 口腔疾病防治, 2022, 30(1): 73-76. doi: 10.12016/j.issn.2096-1456.2022.01.013.
Zhang XJ, Zhang B. Research progress on the application of nanoparticle drug delivery systems in local drug treatment of periodontitis[J]. J Prev Treat Stomatol Dis, 2022, 30(1): 73-76. doi: 10.12016/j.issn.2096-1456.2022.01.013.

（编辑　罗燕鸿）

Open Access
This article is licensed under a Creative Commons Attribution 4.0 International License.
Copyright © 2025 by Editorial Department of Journal of Prevention and Treatment for Stomatological Diseases

官网