净水技术前沿与热点综述

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典型流域视角下地表水体中新污染物的分布、溯源及毒性评估

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摘 要 **【目的】** 新污染物(NPs)已广泛分布于我国河流、湖泊和饮用水源地,对生态系统与公共健康构成长期威胁。本文旨在系统评估我国典型地表水环境中 NPs 的环境分布、来源路径及毒性效应,并剖析我国相关监测与管控的关键措施。**【方法】** 基于 2020 年—2025 年国内外流域 303 组监测数据,采用 Meta 分析、跨介质对比与机制分析相结合的方式,梳理 4 类 NPs 在我国七大板块地表流域中的时空分布格局、主要来源与迁移转化过程;归纳其在水-沉积物-生物体中的富集与复合毒性风险;并结合政策文件,评估现行高通量筛选、风险识别与区域清单制定等环节的技术与管理现状。**【结果】** NPs 在我国水环境中由沿海向内陆逐渐增加,微塑料、抗生素、内分泌干扰物、持久性有机物高污染热点分别聚集在华东、华南、沿海及部分华中/内陆板块、华中以及东北和华北板块。此类污染物源自多种人类活动,对水生生物构成严重毒性,并通过食物链威胁人类健康。尽管我国在 NPs 治理方面已取得初步成效,但在低剂量混合暴露毒性机理解析、高通量非靶向筛查、区域化高风险物质清单编制以及末端治理工艺示范等关键环节仍存在显著短板。**【结论】** 为进一步实现 NPs 的全过程管控,应构建常态化、多介质一体的监测网络并与公共健康数据库联动,推动非靶向高通量分析与机器学习相结合,建立智能筛选与动态更新机制;在国家优先名录基础上制订差异化的高毒性物质分区清单,并通过跨省联防共治提升溯源与治理的精准度;同时加快针对性控制技术的工程化与示范应用,形成从源头减排到末端处置的闭环监管与治理体系。

关键词 新污染物; 水环境; 分布特征; 溯源; 毒性效应
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Distribution, Source Tracing and Toxicity Assessment of Novel Pollutants in Surface Water Bodies under the Perspective of Typical Watersheds

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Abstract [**Objective**] Novel pollutants (NPs) are widely distributed in rivers, lakes, and drinking water sources at home, posing long-term threats to aquatic ecosystems and public health. This paper aims to systematically evaluate the environmental distribution, source pathways, and toxic effects of NPs in typical surface water environments at home and examine key measures for their monitoring and control. [**Methods**] Based on 303 monitoring datasets from river basins at home and abroad from 2020 to 2025, this paper combines Meta-analysis, cross-media comparison, and mechanistic analysis to characterize the spatiotemporal distribution, major sources, and migration and transformation processes of four classes of NPs across surface water basins in seven major regions at home. It further summarizes their accumulation and mixture toxicity risks across water-sediment-biota compartments and, drawing on relevant

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policy documents, assesses the current status of technologies and management practices in high-throughput screening, risk identification, and regional list development. [**Results**] NPs in aquatic environments at home generally increase in concentration from coastal to inland regions. Hotspots of microplastics occur mainly in East China; those of antibiotics in South China; those of endocrine-disrupting compounds in coastal areas and parts of Central China and Chinese Mainland; and those of persistent organic pollutants in Central, Northeast, and North China. These pollutants originate from diverse anthropogenic activities, are highly toxic to aquatic organisms, and threaten human health through the food chain. Although initial progress has made in management of NPs at home, substantial gaps remain in the mechanistic understanding of low-dose mixture toxicity, the development of high-throughput non-targeted screening techniques, the establishment of region-specific lists of high-risk substances, and the demonstration of end-of-pipe treatment processes. [**Conclusion**] To advance whole-process control of NPs, a routine, integrated multi-media monitoring network linked to public health databases should be established, while non-targeted high-throughput analysis should be integrated with machine learning to enable intelligent screening and dynamic updating. Differentiated zonal lists of highly toxic substances should be developed based on the national priority list, and interprovincial joint prevention and control should be strengthened to improve the precision of source tracing and pollution control, and engineering-scale application and demonstration of targeted control technologies should be accelerated to establish a closed-loop regulatory and management system from source reduction to end-of-pipe treatment.

Keywords novel pollutants (NPs); water environment; distribution characteristic; source tracing; toxic effect

随着工业化进程加速,我国 4 类主要化工用品(乙烯、烧碱、合成材料与化肥)的需求量持续增长(图 1)。产业扩张伴随原料、添加剂与副产物的释放,从而推动了新污染物(NPs)的排放[1]。抗生素、内分泌干扰物(EDCs)、持久性有机污染物(POPs)和微塑料(MPs)是国际公认的 4 类 NPs(其分支如表 1 所示),它们通过农业径流、工业排放、生活污水等多种途径进入水体,并经物理、化学和生物转化后形成复合污染。作为全球化学品消耗大国,我国化学品的年用量占世界总量的 1/3 以上[2],伴随而来的是 NPs 在水环境中的持续累积及潜在生态与健康风险加剧[3]。

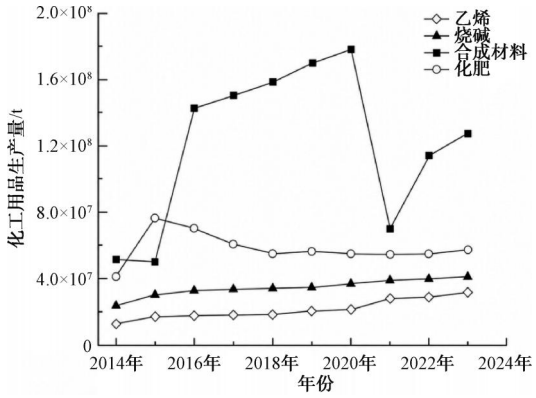


图 1 2014 年—2023 年我国主要化工用品生产量

Fig. 1 Output of Major Chemical Products at Home from 2014 to 2023

表 1 NPs 的分类[4-7]

Tab. 1 Classification of NPs[4-7]

NPs 大类	NPs 中类	NPs 小类
POPs	农药和杀虫剂	有机氯农药如滴滴涕类(DDTs)、六氯环己烷类(HCHs)、马拉硫磷、毒杀芬、氯丹、福美双、甲基对硫磷、敌草隆、胺甲萘
	工业化学品	全氟化合物(PFAS)、多氯联苯(PCBs)、多溴联苯醚(PBDEs)、氯化石蜡、人造甜味剂、有机磷阻燃剂
	工业副产物	多氯二苯并对二噁英、多氯二苯并呋喃
EDCs	激素类	雌激素类、己烯雌酚、雌酮、17β-雌二醇、雌三醇、17α-炔雌醇、雄激素类、肾上腺皮质激素类
	药品和个人护理品(PPCPs)	非甾体抗炎药(萘普生、双氯芬酸)、三氯生
	邻苯二甲酸酯类(PAEs)	邻苯二甲酸二丁酯、邻苯二甲酸二乙酯等
	烷基酚和双酚类	双酚 A、双酚 F、双酚 S、辛基酚、壬基酚
MPs	聚苯乙烯、聚乙烯、聚丙烯等	
抗生素	磺胺类	磺胺甲□恶唑、磺胺嘧啶、甲氧苄啶等

(续表1)

NPs 大类	NPs 中类	NPs 小类
抗生素	喹诺酮类	氧氟沙星、诺氟沙星、帕沙星、环丙沙星
	四环素类	四环素、多西环素、米诺环素等
	氯霉素类	氯霉素及甲砜霉素
	大环内酯类	红霉素、泰乐菌素、克拉红霉素、泰乐菌素
	氨基糖苷类	链霉素、硫酸卡那霉素、庆大霉素、新霉素、阿米卡星
	β-内酰胺类	青霉素类、头孢菌素类、碳青霉烯类等
	林可酰胺类	克林霉素、林可霉素等
	多肽类	粘菌素、杆菌肽等
	糖肽类抗生素	万古霉素、替考拉宁等

自 2015 年《水污染防治行动计划》实施以来,国内外开展了大量关于地表水中 NPs 的相关研究[8-13],并取得重要成果。例如,陈瑞卿等[14]在长江湖北段发现双酚 A 和烷基酚的高质量浓度暴露;Chai 等[15]在白洋淀的研究揭示了 63 种 NPs 在枯/雨季的时空分布及其与人类活动的关联;Monk 等[16]评估了多种药物的生态风险,发现对乙酰氨基酚、布洛芬等风险显著;胡天天等[17]评估了我国污水处理厂(WWTPs)中 NPs 的潜在风险,发现多个地区 WWTPs 存在中到高的生态风险。然而,这些研究普遍存在样本和时空覆盖不足、聚焦单一化合物类群、监测方法异质性高、缺乏近年来流域尺度的系统性评述等问题,制约了我国典型流域 NPs 的全面认知和管控策略的制定。

本文以我国典型流域为案例,采用 Meta 分析结合跨介质对比与机制剖析,系统汇总并量化 4 大类 NPs 在地表水体中的时空分布与迁移转化规律,识别主要来源与关键驱动因子,并在此基础上提出可操作的管控路径与政策建议,以期为公众风险认知提升、水生态安全保障及人类健康防护提供理论支持。

1 水生环境中 NPs 的种类与分布

1.1 文献检索、筛选和数据提取

为系统评估我国地表水中 NPs 的区域分布特征,本文在 Web of Science(WOS)与中国知网(CNKI)上检索 2020 年—2025 年发表的相关文献(检索日与完整检索式如图 2 所示)。初检记录为 WOS=1 027 篇、CNKI=10 815 篇;经题录/摘要筛选并限制发表年限后分别剩余 389 篇与 5 742 篇;全文评估并应用纳入/排除标准后,WOS 纳入 179 篇、CNKI 纳入 44 篇,合计 223 篇,提取 303 组环境质量浓度数据(图 2)。纳入标准为:在我国境内对地表水(河流、湖泊、水库、入海口等)原位采样并报告可提取质量浓度的原始研究,中文或英文,发表时间 2020 年—2025 年,且能换算为统一单位(ng/L 或 μg/L);排除综述、方法学文章、仅为模型/实验室推估且无环境原始质量浓度者,或无法获取/换算为定量质量浓度者。数据按预设标准化表格提取,主要字段包括作者/年、采样时间与地点(省/流域/经纬度)、水体类型、污染物名称与质量浓度指标(几何均值、平均值、范围/区间)、样品相(溶解/颗粒)、分析方法及质量保证/质量控制信息。

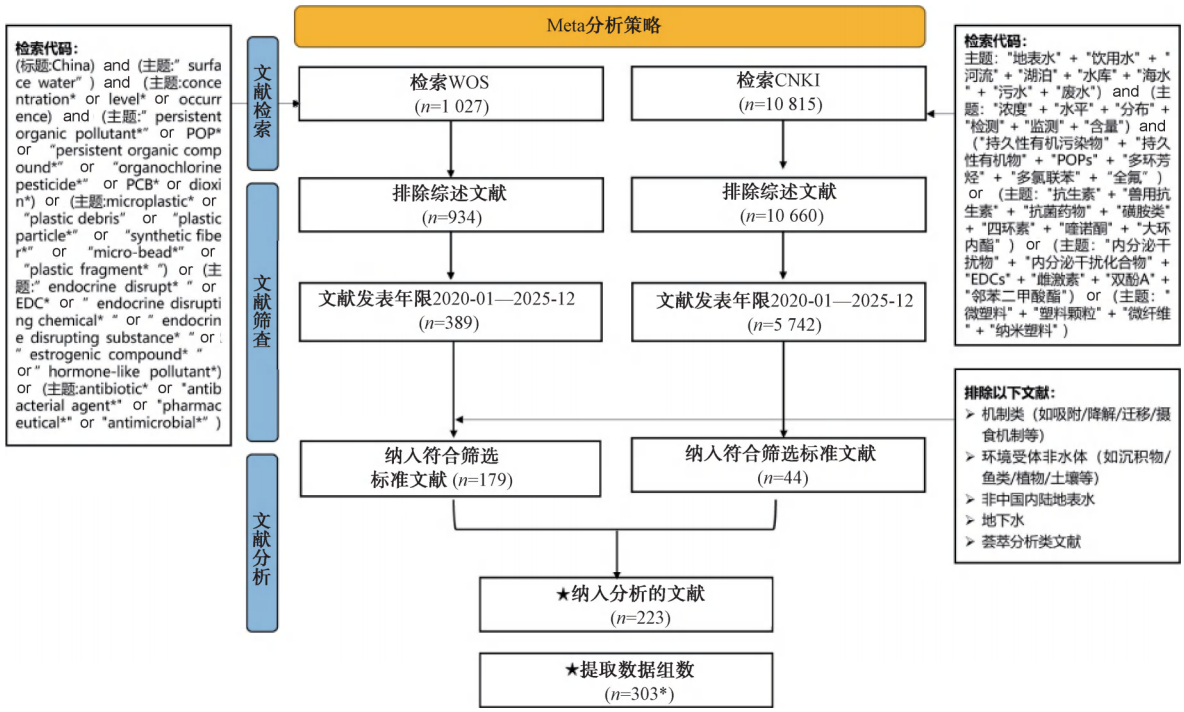
1.2 数据转换和统计分析

1.2.1 数据处理

本文将质量浓度数据按我国七大板块(东北、华北、华东、华南、西北、西南、华中)分类,构成 Meta 分析核心数据集。所有质量浓度统一换算为 ng/L,数据提取优先选择报告区间/范围的值,由于环境质量浓度通常呈对数正态分布,区间数据先在对数空间计算几何均值并折算回原始量纲(本文所报告的几何均值即按此方法计算)。已给出几何均值者直接采用。未检出值以检出限的 1/2 替代。

1.2.2 异质性与偏倚检验

本文以质量浓度对数作为分析尺度,效应量记为 y_i=ln(质量浓度)。当文献同时报告组内标准差(SD)和样本量(n)时,按 Delta 法估算标准误差(SE),并以 y_i 与 SE_i 进行逆方差加权的随机效应元分析(DerSimonian-Laird),报告 Cochran′s Q、T^2 与 I^2。偏倚性评估采用 Egger 回归截距和 Begg(Kendall)检验。鉴于大多数记录未同时给出 SD 与



注:1 组数据指"在特定地理单元(板块/省/河段)"下特定污染物类别(或单一化合物)所报道的质量浓度范围的独立记录;同一研究对不同污染物分别给出质量浓度数据,则作≥1 组提取。

图 2 Meta 分析技术路线

Fig. 2 Technical Route of the Meta-Analysis

n,除上述基于报告 SE 的常规元分析外,还采用 2 类补充检验:一是对按板块分组的对数浓度作 Kruskal-Wallis 非参数检验(不依赖单条观测 SE);二是进行基于假设 SE 的敏感性元分析(用于检验结论对 SE 假设的稳健性),具体采用情形 A [变异系数(CV) = 0.50, n = 3] 和情形 B (CV = 0.25, n = 5),按照 CV 与$\sqrt{n}$之比估算各记录的 SE 再开展随机效应分析。所有基于假设 SE 的结果仅作稳健性提示,并在结果中明确标注其假设前提与局限。统计分析使用 Python (pandas、numpy、scipy、statsmodels、matplotlib);I^2 的解释采用常用阈值(25%、50%、75% 分别代表低、中、高异质性),Cochran′s Q 的显著性参照 p<0.10,Egger 以 p<0.05 提示偏倚。

1.3 总体分布情况

Meta 分析结果如图 3 所示,我国水环境中 NPs 总体由沿海向内陆逐级增加[图 3(a)],华中、华北和西北为相对高污染区。按污染物类分布:POPs 高值集中于中部、东北和华北部分样本,反映历史排放及沉积释放的局部峰值[图 3(b)];抗生素在华东和华南为高值区,华北为中等水平,其他板块较低[图 3(c)];MPs 在华东质量浓度最高,华南、西北和华中次之,东北和华北总体较低,但部分内陆湖泊有显著颗粒峰值[图 3(d)];EDCs 在沿海及部分中部/内陆板块质量浓度较高[图 3(e)]。区域差异受样本水体类型、采样设计、分析方法、时间跨度及样本量等异质性影响,区域差异的解释应结合这些方法学差异与监测覆盖情况加以审慎判断。

(1)POPs 在我国的分布特征

POPs 包括 PFAS、有机磷酸酯、PCBs、多环芳烃(PAHs)、PBDEs、有机氯农药及二噁英等,已在长江流域[18]、珠江三角洲[19]、太湖[20]、辽东湾海域[21]、黄浦江[22]与黄河口[23]等地表水体中被广泛检出,样本质量浓度可达数千 ng/L。以 PFAS 为例,受纺织、食品包装及润滑剂等行业排放影响,已从内陆(如呼伦湖、黄浦江、黄河与太湖[22,24])扩散至莱州湾、胶州湾及深圳-南海近岸海域[25-26],并在饮用水源中多次检出[27-28]。调查[28]显示,国内 17 种 PFAS 的质量浓度为 4.49~175 ng/L,明显高于西方国家。这可能与我国 PFAS 产业产能集中、污水处

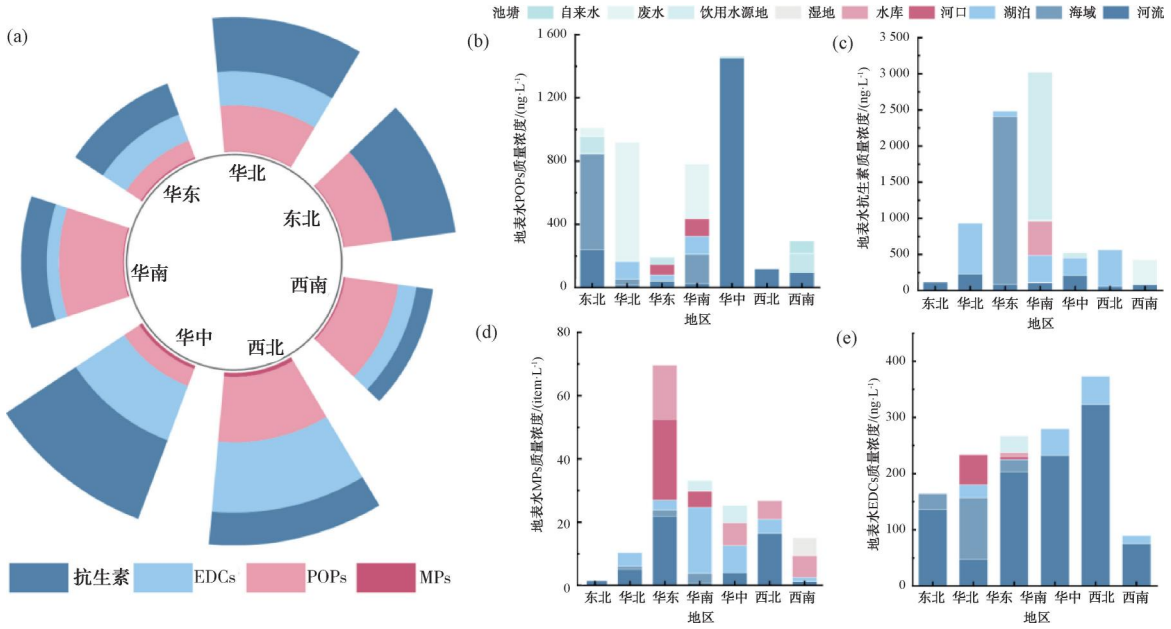


图 3　基于 Meta 分析 NPs 在我国七大区域的赋存特征：(a)4 类 NPs 整体质量浓度水平；(b)POPs；(c)抗生素；(d)MPs；(e)EDCs

Fig. 3　Meta-Analysis-based Occurrence of NPs across Seven Regions at Home: (a) Overall Mass Concentrations of Four NPs; (b) Mass Concentration Distribution of POPs; (c) Antibiotics; (d) MPs; (e) EDCs

理去除效率较低等因素有关，同时历史排放与近岸沉积的再释放也导致局部高含量。PAHs 作为另一类典型 POPs，在河口（如黄河口[23]）、河流（长江[18]、辽江[29]）、湖泊（太湖[30]、升金湖[31]等）及海域（渤海[32]）广泛存在，甚至在武汉、内蒙古等饮用水源地也被检出[33-34]。有机氯农药（如 HCHs、DDTs）及农用化学物（如阿特拉津）亦在我国多类水体中被反复检测到[35-36]。鉴于上述分布与质量浓度特征，亟须自源头减排、强化治理并建立长期监测体系，以降低潜在的生态与健康风险。

（2）抗生素在我国的分布特征

抗生素广泛用于人兽医疗、防治和养殖增效，其在环境中的残留与扩散已成为我国 NPs 研究的核心问题之一。Meta 分析显示，抗生素在我国地表水中的分布广泛。研究表明，我国河流抗生素的平均质量浓度为 303 ng/L，分别是美国和德国的 3 倍和 15 倍[37]，且在辽河[38]、贵州赤水河[39]、汾河流域[40]、北京城市河流[41]等地可达到千 ng/L 级别的高值。此种国际差异可能源于我国用药强度较高、畜禽和水产养殖密集、医疗和农业废水治理不足以及 WWTPs 对抗生素去除效率有限；样本类型、采样时序与检测方法（如代谢物、检出限）也会放大跨国比较差异。除了流域外，国内水库、湖泊、饮用水源、自来水和近岸海域也频繁检出抗生素[42-46]。此外，季节性和流域类型的不一致分布（如冬季高于夏季、旱期高于雨期）及新冠疫情期间的异常升高，进一步揭示了抗生素在环境中的动态演变[26,47]。目前，我国对抗生素污染的认识仍存在空间与时间覆盖不足、监测方法差异及长期监测资料匮乏等盲区，影响了风险评估与治理策略的制定。因此，亟须加强源头减排与治理、提升污水处理效率、建立规范化的监测体系，并将抗性基因纳入常规监测框架，支持基于证据的优先级排序与风险管理。

（3）MPs 在我国的分布特征

常见 MPs 包括聚苯乙烯、聚乙烯、聚丙烯、聚氯乙烯和聚对苯二甲酸乙二醇酯。全球估算[48]显示，2019 年约 610 万 t 废塑料以 MPs 形式进入水体，导致 90%的表层水体受污染；国内研究[37]表明，我国淡水中的 MPs 丰度是多数国家的 2~3 倍，可能与我国快速增长的塑料消费、河流输移与近岸沉积的高通量以及 WWTPs 对微粒截留的局限有关。空间分布上，华东区域污染最为严重，广东沿海海域[49]、黄河[50]、南京秦淮河[51]、华北渤海湾[52]、长江上游嘉堰水库[53]等地亦有高富集，甚至在一些高山湖泊和

偏远水域也出现质量浓度峰值[54],显示出输移与局地沉积过程的复杂性。此外,区域风场、水流和人类活动强度亦显著影响 MPs 的时空分布:城市水源普遍高于农村,旱季高于雨季,洪泛区和水坝周边常见富集现象[50,55]。不同研究所用的采样体积、过滤孔径与分析方法导致检测粒径范围与质量浓度差异,揭示了 MPs 在我国水环境中的非均质分布和多尺度驱动因子,也暴露出采样与分析方法标准化不足的问题。因此,需通过源头减量、提升污水与饮用水处理能力、推广高灵敏度分析方法,并建立统一监测规范与长期观测网络,以提高数据可比性,为精准减排与风险管控提供依据。

(4)EDCs 在我国的分布特征

EDCs 作为能够干扰生物体内分泌系统的外源化合物,在我国水环境中的普遍存在暴露出多重矛盾。除东北板块缺乏报道外,华北、华东、华南、西北、西南与华中六大板块的河流、湖泊、海域、饮用水源地等多类地表水样本均有 EDCs 检出,且在升金湖[31]、太湖[56]、南海北部海域[57]、北运河[58]、淮河下游[59]、洛马湖[60]、东江[61]、汉江中下游[62]等地质量浓度高达数千 ng/L。主要污染物包括 PAEs、壬基酚、双酚类、类激素、PPCPs 等。研究[63]发现,西南成都平原饮用水源与自来水中 PAEs 质量浓度高达 1 788.79 ng/L 和 4 095.89 ng/L,显示局地暴露可能极高。EDCs 的空间-时间差异也受污染源分布、工业与生活排放强度、气候水文条件及降解过程的影响:靠近工业区或生活排放集中的地区常检出较高质量浓度[64];季节性疾病暴发时,药物排放也可能短期提升 EDCs 质量浓度。鉴于多维驱动因素,基于单一靶标的监测与静态模型难以反映 EDCs 的真实暴露轨迹与生态健康风险。为弥补监测盲区并支撑治理决策,应建立标准化采样方案,扩大时空监测网络,引入高通量化学分析与生物效应测定,并将 WWTPs 通量、产销量与社会行为数据纳入联合分析,为 EDCs 的源头控制与综合风险管理提供证据。

(5)分布差异与产业格局的耦合特征

4 类 NPs 在时空上的差异性是污染物特性与流域沿岸产业格局相互作用的产物。总体来看,疏水且易吸附颗粒的 POPs(如 PAHs、PCBs、PBDEs)倾于向在工业密集区、河口沉积区与历史污染热区富集[65],例如长江下游至黄浦江沿岸的化工、纺织与冶金带、辽东湾与山东沿海的重化工与港口带对应 POPs 的局地高值;亲水或耐溶出的化合物(如多数抗生素)则更多反映点源排放强度与污水处理覆盖,常在 WWTPs 密集、医疗/制药产区及畜禽与水产养殖密集流域体现高值[66-67],如辽河、贵州赤水河、汾河与北京城市河流等。MPs 的空间格局则受城市化、纺织与塑料加工、港口与旅游活动驱动[68-69],表现为城市近岸、港湾与旅游热点富集(华东沿海、珠三角近岸、南京秦淮河等为代表);EDCs(如 PAEs、双酚类与某些 PPCPs)则体现出工业-生活混合源特征,既受塑料/包装与表面处理行业影响,也与城市生活排放、医疗与个人护理品使用密切相关(升金湖、太湖与若干城市饮用水源出现的高值即为例证)[70]。

由此可见,板块级的污染高值通常可在更细尺度的流域或河段找到与沿岸产业分布相对应的源支撑:特定的产业聚集区往往对应特定类别的 NPs“热点”。本文在第 2 节将基于已有文献中报告的污染源信息,进一步讨论这些沿岸产业与人类活动对 NPs 分布的驱动作用,以检验上述定性关联的稳健性。

1.4 异质性与偏倚性结果与展望

本文纳入标准化观测 303 条(MPs 为 93 条、POPs 为 68 条、EDCs 为 70 条、抗生素为 70 条)。多数原始记录未同时报告组内 SD 与 n,故不可直接以报告 SE 实施严格的逆方差加权元分析。如表 2 所示,对按板块分组的对数质量浓度进行 Kruskal-Wallis 检验未检出显著区域差异[H(MPs) = 83.299, p = 0.409; H(POPs) = 40.850, p = 0.477; H(EDCs) = 61.483, p = 0.226; H(抗生素) = 41.868, p = 0.563]。以保守假设估算 SE(情形 A:CV = 0.50, n = 3)作为敏感性检验时,大多数类别呈极高异质性(I^2 为 97%~99%),且 Egger 检验显著[p(MPs) ≈ 0.014, p(POPs/EDCs/抗生素) < 0.010],提示在该假设条件下存在小样本效应或报告偏倚。结合子组分析与数据结构可推断总体高异质性主要原因如下。

(1)组内变异显著。同一板块内包含多种水体类型(河段、湖泊、支流等)、不同站位与不同采样时点,这些内部差异往往大于板块之间的中位/均值差异,从而降低按板块检出的显著性;

(2)方法学异质。样品采集方式、前处理流程、分析方法与检出限存在差异,尤其不同研究间检出限和定量策略的差别会显著放大汇总方差;

表 2 各污染物类别样本量、区域差异与异质性/偏倚性检验结果汇总

Tab. 2 Summary of Sample Size, Regional Differences, and Heterogeneity/Bias Tests by Pollutants Classes

污染物类别	K	H	p	I^2(CV=0.50, n=3)	Egger p(CV=0.50, n=3)
MPs	93	83.299	0.409	99.14%	0.014 1
POPs	68	40.850	0.477	98.21%	3.48×10^{-22}
EDCs	70	61.483	0.226	97.91%	7.52×10^{-29}
抗生素	70	41.868	0.563	97.99%	3.61×10^{-30}

注:K 为纳入的标准化观测数量;H 和 p 分别为按板块分组的 Kruskal-Wallis 检验统计量及其对应 p 值;I^2 和 *Egger* p 值基于情形 A(保守假设 CV=0.50, n=3)的敏感性元分析,仅作稳健性提示。

(3)类别内组分差异。将若干不同物质或多个指标合并为 1 类(如 POPs、EDCs)会把性质与来源不同的化合物集合在一起,增加总体变异性;

(4)缺乏权重信息。多数记录缺失 SD/n,使得无法按观测精度进行加权,既影响汇总估计的准确性,也降低区域差异检验的统计功效。

因此,尽管当前数据可用于识别总体分布趋势与相对热点,精确的汇总估计和异质性归因仍受限于原始报告信息的不完备。为提高解释力与可重复性,建议未来研究(或后续元分析)统一报告样本量与组内变异、公开原始观测值,并在元分析中把水体类型、分析方法、采样时点与化合物类别作为分层或元回归协变量以定量分解异质性来源。

2 水生环境中 NPs 的来源与迁移转化机制

板块尺度的质量浓度差异应在更细尺度上追溯其排放通路与迁移转化过程,才能实现合理的归因与治理优先级排序。因此,本节从污染物的典型排放通路和沿岸人类活动入手,概述 4 类 NPs 在源头输入与环境迁移中的主要机制,为 NPs 的精准治理提供理论依据。

2.1 我国地表水 NPs 来源

普遍认为,人工合成化学品和人类活动排放的有毒物质被视为水体 NPs 的主要来源[71],但目前对其从源头到水体的迁移转化过程仍存在显著盲区。各地 WWTPs 虽应用生物膜反应器、纳米技术和高级氧化等工艺去除抗生素、PFAS 和雌激素等 NPs,但仍有大量痕量且高毒性物质无法完全去除,直接进入河流湖泊,形成二次污染[67](图 4)。以 PFAS 为例,其不仅来自氟化物加工厂、氟树脂涂层和金属电镀工业的直接排放[65],还可通过灰尘和地表径流

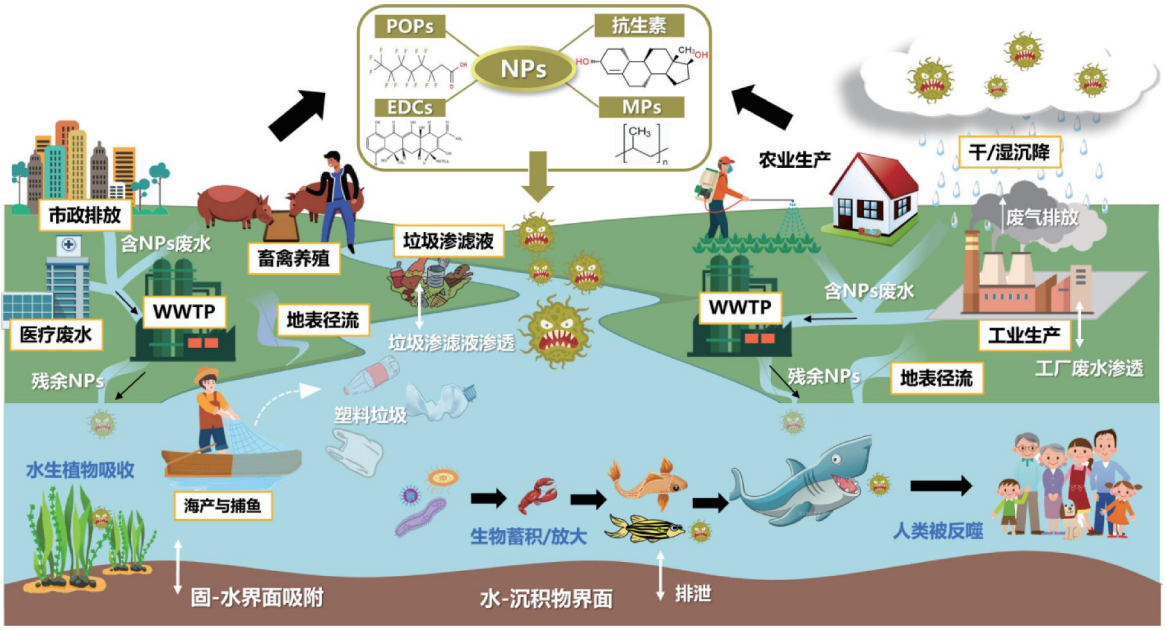


图 4 水环境中 NPs 的来源、迁移及可能的环境影响

Fig. 4 Sources, Migration, and Potential Environmental Impacts of NPs in Water Environment

向水体迁移;有机氯农药则因农药生产、施用及受污染土壤冲刷而持续进入河网;PCBs 主要来自工业废水。抗生素的排放源包括医院废水、制药厂和畜禽养殖废水。Faleye 等[66]研究表明,医疗废水中环丙沙星、氧氟沙星和磺胺甲□噁唑的质量浓度一度高达千余 ng/L;此外,海产养殖区的持续用药更加剧了近岸生态系统的负荷[72]。MPs 作为次生 NPs,其主要来源包括城市与农业塑料垃圾、洗涤用品和纺织品微纤维[68-69],WWTPs 虽可捕集 95%~99%的塑料颗粒,但仍有残余颗粒随出水排放,成为重要输入路径;此外,渔业废弃渔网加剧了海洋 MPs 负荷[73]。EDCs 主要来源于食品包装、药品、增塑剂和表面活性剂的广泛应用[70],同时人畜排泄物、农业径流和医疗卫生设施排放也贡献显著[74-75]。

事实上,NPs 的来源识别的准确性仍面临若干挑战。一是监测覆盖不足,多数流域数据断片化,东北和西北地区监测稀缺,难以实现全国尺度的定量归因;二是分析方法差异,采样设计、靶标谱、检测下限及检出值处理不统一,影响来源判定;三是多污染物协同效应被忽视,不同类别 NPs 在同一流域共存,其相互作用可能改变迁移、转化速率及生物可及性,而现有研究多集中于单一类别,缺乏跨类别耦合的研究;四是缺乏成熟的 NPs 溯源方法,现有模型无法提供统一评价。这些不确定性共同削弱了监测数据的可比性和结论的稳健性。

2.2 NPs 在地表水的迁移转化

为揭示不同类别 NPs 在流域中的主导过程,可将其划分为亲水/溶解性 NPs(如部分 PFAS、PPCPs/EDCs)和疏水/颗粒 NPs(如 PAHs、PCBs、PBDEs 及吸附于 MPs 表面的污染物)。亲水/溶解性 NPs 通过点源排放(如 WWTPs 出水、医疗与养殖废水)、大气沉降、地表径流、土壤渗透及生物迁移进入水体,并迅速扩散。由图 4 可知,它们在水中可经历光降解、水解、生物降解与高级氧化等转化过程,生成毒性较小的产物[76]。然而,部分亲水/溶解性 NPs 具有强迁移性和耐降解性,易在地表和地下水之间跨介质迁移,形成长期污染,其迁移转化速度受分配系数(K_{oc}/log K_{ow})、悬浮固体(SS)/总有机碳(TOC)、水动力条件(流速、径流事件)、温度、光照与氧化还原状态等因素影响[76-78]。疏水/颗粒 NPs 主要通过吸附至 SS 或有机碳进入沉积物库,形成沉积-再悬浮的“汇-源”循环。洪峰、工程扰动或生物活动可能触发沉积物向水相的脉冲释放,产生时空非线性的暴露事件[79]。MPs 不仅是独立污染物,还能作为疏水物质的载体与生物膜基质,改变吸附动力学并促进污染物在生态单元之间的传输[80],为污染物进入更高营养级积累提供重要途径。此外,微生物作用可促使某些污染物降解,而长期低剂量抗生素暴露可能选育和扩散抗性基因,使微生物路径成为迁移与风险的重要通路。

基于上述机理,未来流域监测与治理应聚焦过程导向,采集水相、颗粒相/沉积物与生物体样本,并纳入事件驱动采样,报告关键元数据(如 SS/TOC、流量、过滤孔径及代谢物信息),以便按通量与归一化指标进行比较与模型化。在治理方面,应在源头减排、提升 WWTPs 对难降解污染物及代谢物的去除能力,以及加强沉积物库管理之间协同推进,系统地控制 NPs 的“输入-贮存-释放”全过程。

3 NPs 对人体和环境的毒性效应

与常规污染物相比,NPs 的健康与环境风险具有长期性、隐蔽性和潜在性,所以其带来的环境危害是世界各国普遍面临的难题,NPs 对人体和水生系统的主要危害如图 5 所示。

3.1 人体健康风险

由图 5 可知,人类通过饮用水、食品和空气等途径暴露于 NPs[37]。POPs 因其稳定性和生物富集性,被列为Ⅰ级致癌物,能通过食物链进入人体并损害免疫、神经和生殖系统[81]。如 PFAS 已在水产品、牛奶、肉类及饮用水中长期潜伏,导致癌症、代谢综合征、发育阻滞和生殖影响[48],并可通过母乳和胎盘影响新生儿发育。抗生素在膳食和水中广泛残留,诱发 DNA 损伤、线粒体功能障碍及氧化损伤,是多种疾病的诱因[82],并加剧抗药性问题。据世界卫生组织预测,2050 年将有 1 000 万人因抗生素耐药性大流行而死亡。MPs 及其降解产物已在饮用水、肠道、肺部、血液和骨髓中检出[48,83],能携带 POPs、抗生素和病原体,导致慢性疾病,如呼吸系统和消化系统损伤[84]。EDCs 因亲脂性可在脂肪组织中蓄积,干扰激素合成与受体功能,导致生殖健康障碍,且与内分泌紊乱、甲状腺疾病、流产、肥胖、抑郁等疾病相关[64,85]。总体来看,NPs 的普遍暴露正在从局部健康隐患转变为系统性公共健康挑战。

3.2 环境风险

水生环境中的 NPs 可通过摄食与呼吸被浮游

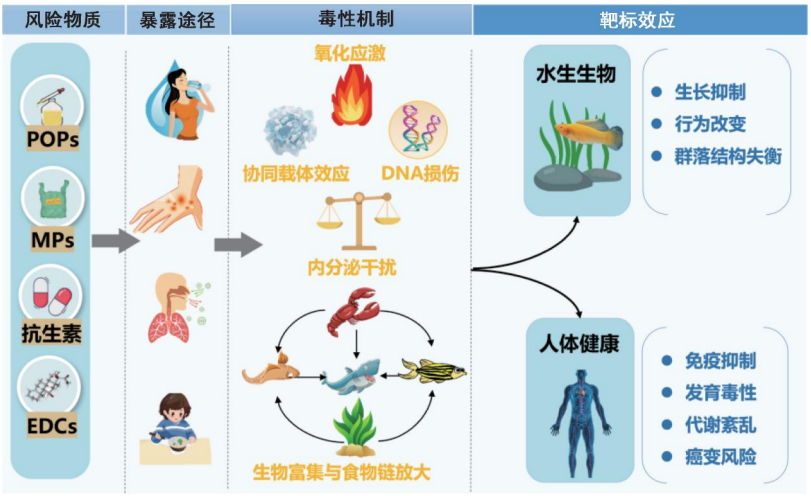


图 5　水环境中 NPs 暴露途径、毒性机制及生态健康效应

Fig. 5　Exposure Pathways, Toxicity Mechanisms, and Ecological Health Effects of NPs in water Environment

生物、鱼类及哺乳动物富集[67]，并对生态系统造成多重影响。POPs(如 PCBs、PFAS 和部分农药)可引发氧化应激、膜损伤和代谢紊乱，抑制生长与繁殖[86]；抗生素因其高生物富集性(log BAF>4)可长期存在于鱼类体内，并导致神经毒性、免疫抑制与抗性基因扩散[67,87]；MPs 在鱼类、软体动物及浮游动物中的检出率高达 85%[88]，可直接损伤肠道、肝脏与鳃，同时作为载体携带 POPs、重金属与病原体，产生叠加风险[89-90]；EDCs 已导致鱼类性别失衡与繁殖力下降，并在某些地区引发高比例的雌雄同体现象[91]。水生植物与藻类方面，PCBs、PFOS、草甘膦、阿特拉津与敌敌畏等通过干扰抗氧化酶、转运系统和光合作用，损害植物与藻类生长[86,92-95]；抗生素主要通过光系统Ⅱ抑制藻类光合作用、叶绿体发育与蛋白质合成[96-97]；MPs 可破坏藻类细胞膜、抑制光合作用并降低次级生产力[98]，与三氯生、壬基酚、双酚等产生协同或拮抗毒性[99]。由此可见，NPs 在多营养级间的累积与交互作用，正在重塑水生生态系统的结构与功能。

3.3　混合暴露的复合毒性现状与展望

现有研究虽揭示了 NPs 对免疫、神经和生殖系统等的损伤，但多数结论依赖单一物质、高剂量或短期实验，难以反映真实的环境情境。事实上，地表水中的化学品通常以低剂量、长期、多物质共存的形式暴露，即便各组分质量浓度低于安全阈值，仍可能因“加和”或“协同”作用产生超预期毒性。例如，研究[100]发现多种雌激素干扰物在低于未观察到不良效应浓度(NOAEC)的混合暴露下仍表现出显著的雌激素活性；此外，雄性小鼠在混合污染暴露后生殖畸形率也显著高于单一物质[101]，表明混合污染是导致风险低估的重要原因。然而，现行风险评估模型难以充分捕捉混合污染物的协同或拮抗效应，以及跨营养级累积和慢性低剂量暴露的复杂性。未来研究亟须结合长期原位监测、多因子协同试验和高通量组学技术，建立能够表征混合污染与多层次毒性的综合评估框架，并辅以流行病学证据链，推动风险评估从单一物质模式向综合化体系转型，为精准治理和公众健康防护提供可靠支撑。

4　研究展望

面对 NPs 在我国的广泛威胁，尽管吸附、膜技术、高级氧化、生物方法和人工湿地等先进治理技术取得初步进展[102]，但与精准控制和综合管控的目标仍有较大差距，基础科学和数据支撑仍显不足。目前，关于 NPs 在多介质中的环境行为、毒性机制及迁移转化的研究较为零散，监测数据库也多集中于个别区域或污染物类型，难以支撑国家层面的风险评估和决策。未来的研究可从以下方面入手。

(1)加大对 NPs 全生命周期研究的投入。整合水、土、气、生物等多介质的常态化监测数据，建立涵盖来源、归趋、转化及生态健康影响的开放式数据库，并推动标准化体系建设，为技术攻关和政策制定提供支持。

(2)完善未知或高风险 NPs 的识别与优先排序机制。传统人工筛选效率低，容易遗漏潜在风险物

质。未来应结合非靶向高通量分析、机器学习预测模型和效应定向生物测定,构建“监测-识别-风险评估-溯源-验证”一体化流程,实现 NPs 的智能筛查与动态更新。

(3)推动高风险 NPs 分区清单。基于区域污染特征和水资源承载能力,制定差异化的高风险 NPs 分区清单,并通过省际联防共治机制,推进跨流域信息共享与协同管控,提升治理精准度和效率。

(4)推动 NPs 去除与修复技术的工程化。尽管单一工艺在去除率上有所优势,但缺乏系统的技术经济评价与规模化示范。应以典型流域为试点,开展中试与示范工程,评估工艺集成与智能化运行效率,同时加快源头控制技术研发,为末端精细化治理提供闭环支持。

(5)促进学科交叉与大数据融合。应深化环境科学、毒理学、信息科学与社会学等学科融合,建立大规模人群队列与生态群落监测平台,结合数字孪生和人工智能工具,实现风险监测、预警与决策支持一体化。只有在“标准化+智能化+区域化+协同化”的框架下,才能逐步实现“监测-治理-风险防控-动态管理”的闭环路径,推动 NPs 的精准管控。

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