◆新污染物与生态环境安全◆

新污染物环境生态效应研究热点*

王晓慧，蒲高忠**
（广西壮族自治区中国科学院广西植物研究所，广西喀斯特植物保育与恢复生态学重点实验室，广西桂林　541006）

摘要：新污染物（Emerging contaminants）是指新发现或新被关注的一类具有生物毒性、环境持久性和生物累积性等特征，并危害人体健康和生态环境安全的污染物（如塑料、纳米材料和抗生素等）。典型代表包括持久性有机污染物（Persistent Organic Pollutants，POPs）、内分泌干扰物（Endocrine-Disrupting Chemicals，EDCs）、抗生素和微塑料。本研究利用 VOSviewe 软件对 Web of Science 数据库进行关键词热点分析，结果显示，当前研究集中在新污染物检测方法和监测技术、生物降解和生物转化机制、生物富集和生物放大效应、生态系统影响和生态风险评估、毒理学效应和修复技术等方面，同时总结了近 5 年新污染物的环境生态效应研究热点，为科研机构和企业等单位提供研究方向，助力新污染物的高效、低成本解决，并为生态环境保护工作中新污染物的防范治理提供理论参考。

关键词：新污染物；生态毒理；生物富集；生物修复

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新污染物（Emerging contaminants）是指新发现或新被关注的一类具有生物毒性、环境持久性和生物累积性等特征，并危害人体健康和生态环境安全的污染物（如塑料、纳米材料和抗生素等）。近年来随着科技、工业及人类活动的发展而出现的新污染物，已经被证实明确存在并对生活和生态环境构成危害。新污染物来源广泛，既可以是工农业生产过程中使用或排放的物质，如工业“三废”（工业生产过程中排出的废气、废水、废渣）、农药、抗生素等，也可以是日常生活中使用的多种物品，如药品、塑料制品、杀虫剂等[1]（图 1）。这些污染物通常与生产生活密切相关，可能是人们长期使用的产品，也可能已在环境中存在多年直到最近才被发现[2]。新污染物通过多种途径进入环境中，在生物个体中富集并随着食物链迁移，严重威胁生物健康和生态安全（图 1）。

新污染物具有隐蔽性、持久性和难以治理等特

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【第一作者简介】
王晓慧（1996—），女，博士，助理研究员，主要从事修复生态学与环境生态学研究，E-mail：wangxiaohui_1996@163.com。
【**通信作者简介】
蒲高忠（1980—），男，博士，研究员，主要从事环境生态学研究，E-mail：pukouchy@163.com。

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征。这些污染物通常化学结构稳定,难以在环境中降解,并能通过食物链不断积累、迁移和扩散[3]。例如,持久性有机污染物(Persistent Organic Pollutants,POPs)、抗生素和内分泌干扰物(Endocrine-Disrupting Chemicals,EDCs)等新污染物,即使在低浓度下也能影响生物的生殖和发育,甚至可能导致物种灭绝[4,5]。然而,一些新污染物被广泛使用,难以找到替代品,且其治理需要跨行业合作,导致治理困难。此外,一些新污染物在环境中的浓度低且分布分散,也增加了治理的难度[6]。因此,亟需总结新污染物的环境生态效应研究热点,为高校、科研机构和企业提供研究方向方面的参考,从而为高效、低成本解决新污染物问题提供理论支持。

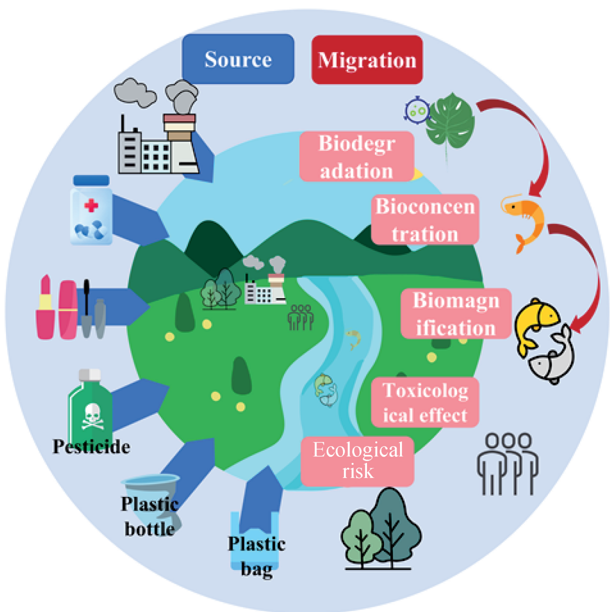

图 1 新污染物环境来源与迁移示意图

Fig.1 Schematic diagram of source and migration of emerging contaminants from the environment

1 典型新污染物

与传统污染物不同,新污染物是被人们发现和“新”认识的一类污染物,这也意味着新污染物不仅种类繁多,并且还会随着社会的发展、科技的进步、检测技术的更新等原因持续增加[7]。为应对这一挑战,我国根据国际社会的关注度与自身国情先后制定了《优先控制化学品名录》、《重点管控新污染物清单》、《关于持久性有机污染物的斯德哥尔摩公约》等化学物品管控名录,对新污染物进行相关的禁止、限制和排放控制[8]。目前,持久性有机污染物、内分泌干扰物、抗生素和微塑料是国际社会高度关注的新污染物。

2 新污染物关键词热点分析

在 Web of Science 数据库中选择核心合集,以“emerging contaminants”为主题,限定年份为“2018-2023 年”,选择语言为“英语”,文章类型为“研究论文”,共检索到 12 581 条记录。使用 VOSviewer 软件对这些结果进行可视化分析,结果显示关键词分为 7 个集群。其中,出现频率超过 100 次的有两个集群(图 2)。第一个集群主要涉及新污染物的吸附及毒理响应(如 Adsorption 和 Reaction mechanism)。第二个集群主要关注微塑料(Microplastics)、持久性有机污染物(POPs)等新污染物对人类健康和生态环境安全(如 Food chain、Health risk、Environmental risk)的负面影响。其他集群则涉及新污染物的检测技术(如 GC-MS)、污染物去除效率(Removal efficiency)以及生物修复技术(如 Phytoremediation)等。综合新污染物出现、影响及修复的规律,当前的研究热点包括:新污染物检测方法和监测技术、生物降解和生物转化机制、生物富集和生物放大效应、生态系统影响和生态风险评估,以及毒理学效应和修复技术研究。

3 新污染物环境生态效应研究的热点

3.1 新污染物检测方法和监测技术

3.1.1 检测方法

目前,典型新污染物的检测主要采用色谱法、光谱法、免疫检测法和电泳法等方法(表 1)。然而,这些方法在定量分析上存在困难,且耗时较长,技术尚不完善,并且环境检测方法和技术规程仍有较大缺口。因此,亟需开发新污染物的检测方法和技术,配备诸如飞行时间质谱、轨道阱质谱等前沿分析仪器,建立全面的新污染物检测体系。

3.1.2 在线监测技术

目前,环境监测的主要技术手段为遥感监测。遥感技术利用卫星、无人机和地基遥感设备,对大范围地表进行实时监测。遥感技术除了能够反映植被指数和地表反射率等数据外,还可以分析污染源和排放量等信息[11]。Evans 等[12]提出一种新的方法,利用美国宇航局的旋风全球导航卫星系统(Cyclone Global Navigation Satellite System,CYGNSS),以及双基地雷达跟踪海洋中的微塑料,这种方法可以用于实时了解微塑料浓度。然而,新污染物的在线监测技术报道目前还相对较少,监测方法仍不成熟。因此,

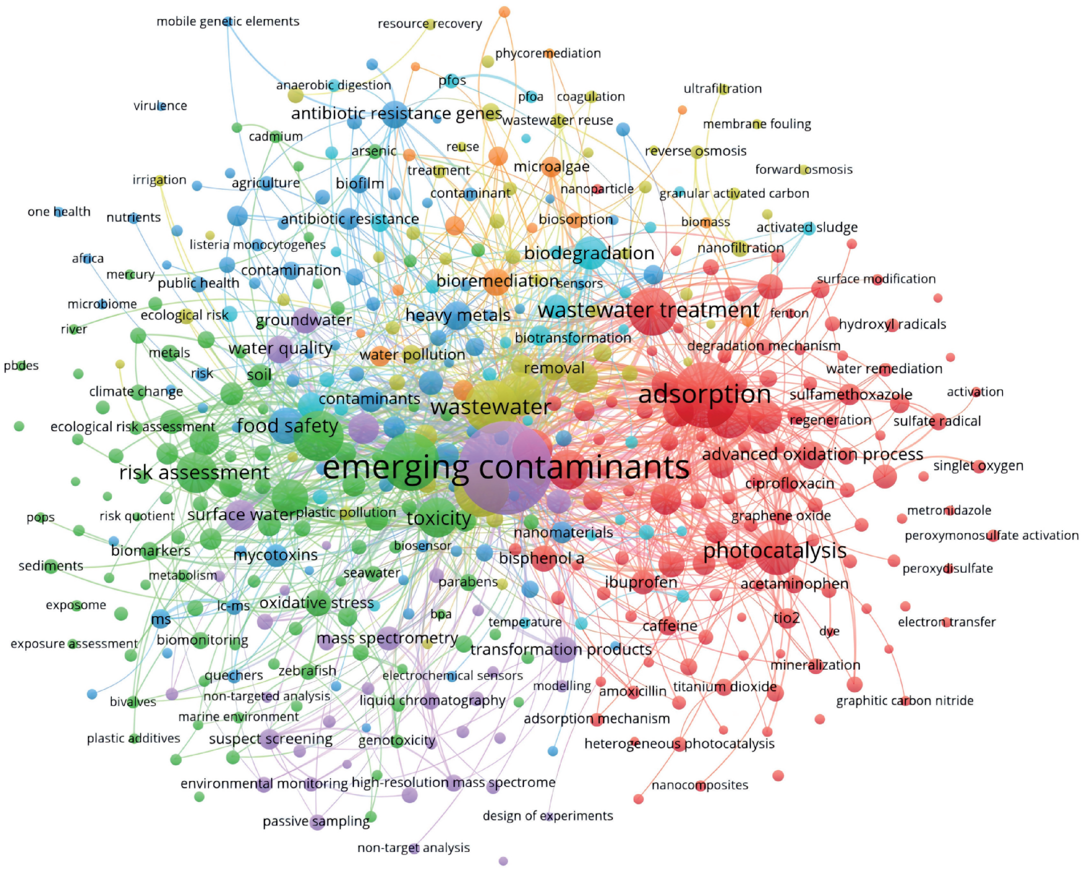

图 2　2018—2023 年新污染物环境生态效应领域关键词网络图

Fig. 2　Keyword network diagram of the field of environmental and ecological effects of emerging contaminants from 2018 to 2023

表 1　环境中典型新污染物的检测方法

Table 1　Detection methods for typical emerging contaminants in the environment

污染物类型 Pollutant type	检测方法 Detection methods	具体技术 Specific technology
Persistent Organic Pollutants (POPs)	Chromatography[9]	High Performance Liquid Chromatography (HPLC), Gas Chromatography (GC), Gas Chromatography-Mass Spectrometry (GC-MS), High Performance Liquid Chromatography-Mass Spectrometry (HPLC-MS), Supercritical Fluid Chromatography (SFC)
	Biological method	Capillary Electrophoresis (CE), biological detection techniques and immunological detection methods
Endocrine Disrupting Chemicals (EDCs)	Chromatography	GC, HPLC, GC-MS, HPLC-MS
	Spectroscopy	Infrared Spectroscopy (IR), Ultraviolet-Visible Spectrophotometry (UV-Vis)
	Biological method	Enzyme-Linked Immunosorbent Assay (ELISA), Radioimmunoassay (RIA), CE, biosensors
Microplastics	Spectroscopy	IR, Raman spectra, hyperspectroscopy and terahertz spectroscopy
	Mass spectrometry	Pyrolysis gas chromatography-mass spectrometry and time-of-flight secondary ion mass spectrometry[10]
	Other methods	Thermogravimetric analysis and microscopic analysis (such as optical microscopy and electron microscopy)
Antibiotics	Chromatography	Liquid Chromatography (LC), High Performance Liquid Chromatography Fluorescence (HPLC-FL), High Performance Liquid Chromatography Ultraviolet (HPLC-UV), and Liquid Chromatography-Mass Spectrometry (LC-MS)
	Biological method	ELISA, radioimmunoassay, and CE

科研人员应进一步研究和开发新污染物的在线监测技术和设备,实现对污染物的实时监测和动态管理,以辅助环保部门更有效地监管环境污染。

3.2 生物降解和生物转化机制

3.2.1 生物降解途径

环境中存在能够降解新污染物的微生物。其中包括应用范围广泛但是仅适用于低浓度污染的降解菌,以及能力强大甚至能够同时降解复合污染物的功能菌[13]。一般具有降解功能的微生物主要从污染环境中分离获得。Li等[14]在污水处理厂污水样品中分离出一株以二甲双胍为唯一生长碳、氮源的氨基杆菌属(*Aminobacter* sp.)菌株NyZ550,其与表达鸟苷脲水解酶的恶臭假单胞菌PaW340(*Pseudomonas putida* PaW340)组成微生物混合物,可用于完全消除二甲双胍及其持久性产物鸟苷脲。Li等[15]发现红球菌BX2(*Rhodococcus rhodochrous* BX2)对三氯卡班具有有效的降解和矿化能力,通过基因组学和转录组学确定该菌株存在一条进入TCA循环的三氯卡班生物降解通路,*TccS*和PH_{IND}基因分别是三氯卡班及其中间体4-CA转化的必要基因。这为使用特定菌株装载降解基因构建新的基因工程菌株以实现污染物的有效生物降解奠定基础。总之,生物降解在新污染物的去除中占据重要地位。

3.2.2 生物转化机制

新污染物在生物降解过程中产生的转化产物和代谢产物也可能具有生物毒性。如抗惊厥药物卡马西平(CBZ),其副产物(CBZ-BPs)的毒性超过CBZ,预测毒性累积模型(PTAM)的预测结果表明,吖啶结构对其毒性有重大贡献[16]。此外,对乙酰氨基酚消散和转化途径会形成大量中间体(包括3-羟基对乙酰氨基酚、对苯二酚、1,4-苯醌、*N*-乙酰基对苯醌亚胺、对乙酰氨基、4-甲氧基苯酚、2-己烯酸和1,4-二甲氧基苯),这些中间体具有潜在的生物活性,可能会带来未知的风险[17]。此外,传统的生物处理工艺也可能将新污染物转化为高毒转化副产物,如硝基咪唑类抗生素[18]。因此,有必要升级治理和修复技术以达到消解新污染物的同时降低其转化产物生物毒性的目的。

3.3 生物富集和生物放大效应

3.3.1 生物富集特征

新污染物能够在生物体内积累,并且其富集特征和规律受到污染物类型及生物种类的影响。新污染物可以被植物吸收并积累在植物组织中。例如,克拉霉素、卡马西平、美托洛尔、氟康唑和甘巴唑会在番茄(*Solanum lycopersicum* L. cv Taylor F1)中大量富集[19]。新污染物还能够进入动物体内并积累在组织中。研究发现,印度河系统主要支流可食用鱼类的肌肉组织中累积了一定量的全氟烷基和多氟烷基物质[20]。新污染物也可以通过吸附作用附着在生物表面。Boldrocchi等[21]研究表明,大型滤食性鲨鱼姥鲨(*Cetorhinus maximus*)的真皮小齿上吸附了很多新污染物。此外,微塑料等新污染物还能够促进其他污染物(如芘)在生物体内的积累[22]。微塑料甚至可作为污染物的转运载体和有毒物质的化学增敏剂[23]。新污染物不仅会在生物体内或体表积累,还会通过食物链迁移,从而破坏生态系统的稳定性。

3.3.2 生物放大效应机制

新污染物在食物链中的传递具有生物放大效应。如微/纳米塑料(MNPs)与重金属的复合污染可以通过微生物循环和经典食物链传递至顶端捕食者,转录组学分析显示,新污染物会刺激诱导P13K-Akt等通路的异常调节,使生物发生细胞凋亡或者炎症反应[24]。摄食是新污染物进入食物链的主要途径,“从饲料到食物”也是人类接触新污染物的主要途径之一,这些污染物通过食物链的流动可能会造成人类细胞氧化损伤和坏死[25]。此外,环境因素和环境介质是影响新污染物在食物链中迁移的主要因素。研究表明,鄱阳湖水生食物链中有机磷酸酯的动态受到水温控制[26]。新污染物在土壤中的迁移和转化过程交织复杂,这增加了微塑料和有机农药等污染物毒理的不确定性。因此,有必要深入解析新污染物的迁移过程,了解其累积和转移规律,以评估生态系统的风险和稳定性。

3.4 生态系统响应和生态风险评估

3.4.1 生态系统响应

新污染物对生态系统结构和功能有负面影响。例如在水生生态系统中,Larrea Murrell等[27]在古巴西部Almendares河和San Juan河中检测出抗高血压药、兴奋剂、抗炎药和抗生素等新污染物,这些污染物可抑制蛋白酶、磷酸酶和脂肪酶的活性,并增强过氧化氢酶活性以应对氧化应激。Du等[28]对河口沉积物的研究发现,嗜盐囊菌属(*Haliangium*)、交替赤细菌属(*Altererythrobacter*)和盖氏菌属(*Gaiella*)等细菌可以作为新污染物的潜在污染指标。然而,生态系统有强大的自修复和保持稳态的能力。Wolff等[29]利用人工湿地去除废水中的新有机污染物,为

污染物去除提供了一种有效的替代技术。尽管如此，仍然需要挖掘更多高效、环保、经济的技术手段帮助生态系统恢复洁净。

3.4.2 生态风险评估

生态风险评估和预测需要综合考虑新污染物的毒性效应、生物富集特征和生物放大效应。此外，相应的环境保护措施和管理策略也至关重要。国际上主流的环境管理主要是源头管控和环境监测两种途径，通过筛查生产和使用中的化学物质、调查环境介质中污染物的检出情况，对新污染物实施观察、评估、管控等措施[30]。我国也建立了自己的新污染物管控体系。截至2023年底，我国已经全面淘汰了短链氯化石蜡等8种类别的重点管控新污染物的生产、加工使用和进出口[31]。未来，应继续坚持对新污染物进行精准治污，科学管理，加快推进化学物质环境管理立法，并建立健全新污染物治理制度体系。此外，各科研单位还应加强科研攻关，为新污染物的精准治理提供科技支持。

3.5 毒理学效应和修复技术

3.5.1 毒理学效应

新污染物对生物的生长发育和生理功能等均产生不同程度的负面影响。于植物而言，新污染物会对其光合作用、养分吸收和生长发育等关键过程造成负面影响[32,33]。而植物也会激活自身的防御机制应对这些胁迫。Martins等[34]研究发现，在双氯芬酸胁迫下，番茄会牺牲地上部的碳储量，增强根部谷氨酰胺合成酶和谷氨酸脱氢酶的活性，以维持重要的补偿途径。于动物而言，新污染物的毒害作用主要表现为动物生殖系统、免疫系统和神经系统的功能异常[35]。此外，与单一污染物相比，由不同新污染物组成的复合污染物对生态系统的危害更大。Li等[36]研究表明，微塑料与抗生素的联合污染会严重破坏植物的根系生长、抗氧化酶系统和植物激素途径。Xian等[37]研究发现，微/纳米塑料增强了4-甲基亚苄基樟脑(4-MBC)在斑马鱼组织中的积累，并对其神经和生殖系统造成性别特异性的损伤。因此，研究复合新污染物的毒性机制和作用途径对于制定相应的治理策略至关重要。

3.5.2 修复技术

环境中新污染物的修复方法包括物理修复法、化学修复法和生物修复法等多种方法(表2)。可根据不同类型的污染物和污染场地选择合适的修复方法，以实现对新污染物的高效、安全、经济治理。尽管物理修复法和化学修复法具有周期短的优势，但其高昂的修复成本和易造成二次污染的风险掣肘其在实际中的应用[41]。相比之下，生物修复法因其环境友好、不易造成二次污染以及价格低廉等优势而受到广泛关注。如丛枝菌根真菌(Arbuscular Mycorrhizal Fungi，AMF)联合超富集植物修复农药、微塑料等污染的研究已经被广泛报道[42,43]。在实际应用中，通常将几种修复方法结合使用，以最大程度提高修复效果。因此，探索新污染物的生态修复技术和方法至关重要，这将有助于实现对污染环境的修复和恢复，从而提升环境质量和生态健康水平。

表2 环境中新污染物的修复方法

Table 2 Remediation methods for emerging contaminants in the environment

类型 Types	具体措施 Specific measures	适用范围 Scope of application	优势 Advantages	劣势 Disadvantages
Physical repair method[38,39]	Nanomaterial adsorption technology	It can be used to treat heavy metals, organic pollutants, and dyes in groundwater, soil, and wastewater	Easy to operate, no need to add chemical agents, efficient and fast, no by-products produced, and widely applicable	Limited removal efficiency, inability to degrade pollutants, inability to apply to all types of pollutants, requiring significant investment, and inability to maintain long-term stable control of pollutants
	Ultrasonic technology	It can be used to treat organic pollutants, heavy metal ions, etc. in wastewater		
	Magnetic nanoparticle technology	It can be used to treat heavy metals, organic pollutants, etc. in groundwater, soil, and wastewater		

续表

Continued table

类型 Types	具体措施 Specific measures	适用范围 Scope of application	优势 Advantages	劣势 Disadvantages
Chemical repair method	Electrochemical technology	This includes methods such as electrodynamic extraction, electrochemical reduction, electrochemical oxidation, and electro adsorption, which can be used to treat organic pollutants, heavy metals, etc. in wastewater and soil	Efficient degradation of pollutants, targeted treatment of different pollutants, achieving high treatment efficiency, direct treatment of pollution sources, and wide applicability	Possible by-products, high cost of chemical agents, potential impact on non target substances, high technical requirements for operation, and inability to completely remove pollutants
	Photocatalytic remediation technology	It can be used to treat wastewater and organic pollutants, heavy metal ions, etc. in the atmosphere		
	Advanced oxidation repair technology	It can be used to treat wastewater and organic pollutants, heavy metal ions, etc. in the atmosphere		
Bioremediation[40]	Plant remediation technology	It can be used to treat heavy metals, organic pollutants, etc. in soil and water bodies	Environmentally friendly, capable of completely degrading pollutants, with a wide range of applications, good sustainability, and low cost	The repair process is slow, greatly affected by environmental conditions, difficult to control biological activity, may produce by-products, and has limited applicability
	Microbial remediation technology	It can be used to treat organic pollutants, heavy metals, etc. in soil, groundwater, and wastewater		

4 展望

在新污染物环境生态效应研究领域,学术界重点关注的污染物包括微塑料、抗生素、内分泌干扰物、全氟化合物、溴代阻燃剂和纳米材料。通过关键词热点分析,可以总结出该领域的研究热点主要集中在以下方面:新污染物检测方法和监测技术、生物降解和生物转化机制、生物富集和生物放大效应、生态系统影响和生态风险评估,以及毒理学效应和修复技术。目前新污染物研究领域存在一些局限。从生物毒性的研究来看,大多集中在实验室模拟阶段,研究对象单一、污染剂量高、时间短。未来应开展更为系统的机理性实验研究,深入了解新污染物的污染机制。从生态响应来看,在实际环境中的长期跟踪实验有待增加,以全面评估新污染物在不同环境介质下对生物个体、群落和生态系统的影响。未来不仅要对现有研究热点进行补充和拓展,还应该寻找新的研究方向以探究新污染物的复杂生态效应。如气候变化(CO_2浓度升高)、特殊地貌(如喀斯特地貌)、极端环境(高寒、干旱地区)等条件下新污染物在生物体内的累积与毒理效应、食物链的迁移途径、生态系统的响应等。总之,不仅要关注当前环境科学领域中备受关注的热点问题,还要继续努力深入探究新污染物对生态系统的影响及其潜在机制,以指导环境保护和管理实践。

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Research Hotspots on Ecological Effects of Emerging Contaminants on the Environment

WANG Xiaohui, PU Gaozhong**
(Guangxi Key Laboratory of Plant Conservation and Restoration Ecology in Karst Terrain, Guangxi Institute of Botany, Guangxi Zhuang Autonomous Region and Chinese Academy of Sciences, Guilin, Guangxi, 541006, China)

Abstract: Emerging contaminants, or contaminants of emerging concern, are a class of contaminants (such as plastics, nanomaterials, and antibiotics) characterized by biotoxicity, environmental persistence, and bioaccumulation, posing a threat to human health and eco-environment safety. Typical examples of these contaminants include Persistent Organic Pollutants (POPs), Endocrine-Disrupting Chemicals (EDCs), antibiotics, and microplastics. VOSviewer was used to analyze keywords of this field in the Web of Science. The results indicated that available studies of emerging contaminants predominantly focused on the detection and monitoring, mechanisms of biodegradation and biotransformation, bioaccumulation and biomagnification, ecological impacts and risk assessment, toxicological effects, and remediation technologies. This paper summarizes the research hotspots on the environmental and ecological effects of emerging contaminants over the past five years, aiming to provide strategic directions for research institutions and industry stakeholders, support the efficient and cost-effective mitigation of emerging contaminants and offer theoretical guidance for their management in ongoing and future environmental protection efforts.
Key words: emerging contaminants; ecotoxicology; bioaccumulation; bioremediation.

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