

赵思凯,刘沅鑫,梁越,等.水厂消毒中微塑料的赋存、去除及潜在风险[J].中国环境科学,2025,45(4):2208-2219.

Zhao S K, Liu Y X, Liang Y, et al. Occurrence, removal and potential risks of microplastics in disinfection processes of water treatment plants [J]. China Environmental Science, 2025,45(4):2208-2219.

水厂消毒中微塑料的赋存、去除及潜在风险

赵思凯¹,刘沅鑫¹,梁越¹,刘聪²,李家杰³,陈士凌⁴,陈曦¹,吕露¹,李北雁¹,余薇薇^{1*} (1.重庆交通大学海学院,水利水运工程教育部重点实验室,重庆 400074; 2.西南技术工程研究所,重庆 400039; 3.浙江工业大学工程设计集团有限公司,浙江 杭州 310014; 4.重庆建筑工程职业学院,重庆 400072)

摘要: 本文综述了国内外水厂消毒工艺中微塑料(MPs)的赋存特征和丰度情况,分析了氯、臭氧和紫外线消毒对MPs的去除效果,并深入探讨了MPs的存在对消毒的影响及其二次污染.结果发现,不同水厂消毒中MPs丰度具有较大差异,主要以纤维、碎片形状存在,以聚对苯二甲酸乙二醇酯(PET)、聚乙烯(PE)和聚丙烯(PP)为主,粒径大部分小于1.0mm,颜色多呈黑白和透明.氯消毒单元去除率在0~71.38%,但在部分水厂的臭氧消毒和紫外线消毒后,MPs丰度反而上升.消毒工艺对MPs的去除机制仍有待研究.此外,其释放的溶解性有机物(MP-DOM)在氯消毒过程中生成三氯甲烷的潜能(THMFP)最高可达453.3 $\mu\text{g}/\text{mg}$,高于典型水生天然有机物和藻类有机物的生成潜力,显示出更大的健康风险.

关键词: 微塑料; 水处理消毒; 去除效果; 灭菌影响; 二次污染

中图分类号: X503 文献标识码: A 文章编号: 1000-6923(2025)04-2208-12

Occurrence, removal and potential risks of microplastics in disinfection processes of water treatment plants. ZHAO Si-kai¹, LIU Yuan-xin¹, LIANG Yue¹, LIU Cong², LI Jia-jie³, CHEN Shi-ling⁴, CHEN Xi¹, LYU Lu¹, LI Bei-yan¹, YU Wei-wei^{1*} (1.Key Laboratory of Water Conservancy and Water Transport Engineering, Ministry of Education, Hehai College, Chongqing Jiaotong University, Chongqing 400074, China; 2.Southwest Technical Engineering Research Institute, Chongqing 400039, China; 3.Engineering Design Group Co. Ltd., Zhejiang University of Technology, Hangzhou 310014, China; 4.Chongqing Jianzhu College, Chongqing 400072, China). *China Environmental Science*, 2025,45(4): 2208~2219

Abstract: This paper reviewed the occurrence characteristics and abundance of microplastics (MPs) in disinfection processes of water treatment plants both inside and outside China, and analyzed the MPs removal effectiveness of chlorine, ozone and ultraviolet disinfection, followed by an in-depth discussion of the effects of MPs presence on disinfection and its secondary pollution. The results showed significant differences in the abundance of MPs across different water treatment plants, primarily existing in the forms of fibers and fragments, predominantly composed of polyethylene terephthalate (PET), polyethylene (PE), and polypropylene (PP), with most sizes less than 1.0mm and colors mostly black, white, or transparent. The removal rate of the chlorine disinfection unit ranged from 0% to 71.38%; but part of the water treatment plants had seen a rise in MPs abundance after the ozone and ultraviolet disinfection. The removal mechanisms of MPs by disinfection processes remained required further research. Additionally, the trihalomethane formation potential (THMFP) of microplastic-derived dissolved organic matter (MP-DOM) in the chlorine disinfection process could reach as high as 453.3 $\mu\text{g}/\text{mg}$, higher than the formation potential of typical aquatic natural organic matter and algae organic matter, pointing to greater health risks.

Key words: microplastics; water treatment disinfection; removal effect; sterilization impact; secondary pollution

塑料因其成本效益和易用性被广泛用于各个领域,目前全球每年的塑料总产量已增至近4亿t,预计到2050年会翻一番^[1].大部分塑料制品在使用后废弃在自然环境中,并在机械磨损、光照、氧化、水力、微生物和其他风化作用下破碎成粒径小于5mm的微塑料(MPs).多项研究表明,MPs对生态和人体健康安全有诸多不利影响,包括抑制微藻的生长和光合作用^[2-3],导致斑马鱼肠道损伤和代谢紊乱^[4],甚

至诱导人体细胞产生氧化应激或炎症反应^[5].同时,MPs表现出高环境持久性和长距离迁移特点,中已在全球污水处理厂(WWTPs)和饮用水厂(DWTPs)普遍检出^[6].然而现有水厂(包括污水处理厂和饮用

收稿日期: 2024-08-26

基金项目: 重庆市教委科学技术研究项目(KJQN202404306);重庆市研究生联合培养基地建设项目(JDLHPYJD2022005);国家自然科学基金资助项目(51608079)

* 责任作者, 教授, yu11237@cqjtu.edu.cn

水厂)并不能完全去除污水和饮用水中的 MPs,去除率分别在 21.8%~99.8%和-12.7%~99.94%^[7].由于不同工艺的水厂去除效果有差异,且总处理量大,每日仍有大量 MPs 不可避免的排放至水环境中^[8],一个规模 385m³/h 的小型污水处理厂日排放量可达 7.5×10⁸ 个/d^[9].

消毒作为水处理中的最后一道工艺,是防止水中微生物引发疾病的重要屏障.但残留的 MPs 将在消毒过程中显著降低微生物灭活效果,增加病原体和抗性基因传播风险.消毒工艺还能对 MPs 表面产生氧化作用^[10],释放更多溶解性有机物(DOM)^[11].这些 DOM 与水中消毒剂反应,将生成具有致畸、致癌和致突变特性的消毒副产物^[12].MPs 对病原体灭活和二次污染物生成的影响,与其特性及所采用的消毒工艺类型密切相关^[13-14].但目前对于消毒工艺中 MPs 的特征、去除效果及其潜在风险等还未有系统的综述.深入了解水处理消毒中 MPs 的污染,对全面

评估 MPs 排放风险,保证出水水质安全均具有重要意义.基于此,本文总结了国内外水厂消毒工艺中 MPs 的赋存特征,对比了氯、臭氧和紫外线消毒工艺对 MPs 去除效果的差异,揭示其分布规律及去除差异可能的影响机制;深入探讨了 MPs 对消毒效率和副产物生成的双重影响,旨在为优化水处理工艺、科学评估 MPs 排放风险提供一定参考依据.

1 消毒工艺中 MPs 的赋存特征

1.1 MPs 成分

水厂消毒工艺中存在多种 MPs,包括:聚丙烯(PP)、聚乙烯(PE)、聚苯乙烯(PS)、聚对苯二甲酸乙二醇酯(PET)、聚酰胺(PA)、聚氨酯(PU)、聚氯乙烯(PVC)和聚酯纤维(PES)等.其中,PET、PE 和 PP 是污水处理厂和饮用水厂消毒中最为常见的 3 种 MPs (表 1),其与这些塑料在日常生活中的广泛使用与处置方式密切相关.

表 1 国内外水厂消毒工艺中 MPs 的特征

Table 1 Characteristics of MPs in the disinfection process of domestic and foreign water treatment plants

水厂类型	国家	处理工艺	工艺进水丰度 (个/L)	工艺出水丰度 (个/L)	颜色	成分	形状	粒径(μm)	文献
污水处理厂	中国	氯消毒	34.1±9.4	28.4±7.0	透明 (57.6)	PA (54.8)	纤维 (56.5)	20~300 (63.9)	[22]
					棕色 (18)	PP (9.6)	碎片 (30.4)	300~1000 (29)	
					黑色 (10)	PE (9.0)		1000~2000 (5.5)	
	氯消毒	30.1±8.2	22.9±7.2	黑色 (52.5)	PP (33)	纤维 (47.9)	0~100 (81.5)	[32]	
				红色 (23.9)	PE (23)	碎片 (21.8)	100~500 (13.4)		
				透明 (22)	PS (18)	薄膜 (17.3)	500~1000 (3.8)		
	紫外线消毒	19.67±0.94	17.33±1.25	—	透明 (54.3)	PE (38)		<500 (69.5)	[33]
					黑色 (35.5)	PS (32)	纤维 (96.6)	500~1000 (17)	
						PP (20)		1000~2000 (6.8)	
						PET (47)			
紫外线消毒	0.01	0.13±0.01	—		PS (20)	纤维 (100)	125~250 (100)	[19]	
					PE (18)				
					PP (15)				
紫外线消毒	37.9±8.5	30.6±7.8	—	透明 (47.3)	PA (20.5)	纤维 (54.3)	20~100 (42.7)	[34]	
				灰色 (35.9)	PET (14.3)	碎片 (34.3)	100~500 (48.5)		
					PE (11.6)		500~1000 (4.0)		
				黑色 (36)	PE (31.03)	纤维 (84)	80~550 (43.3)		
				红色 (23)	PP (24.14)	碎片 (16)	550~1700 (40.5)		
紫外线消毒	1.85	2.9	—	蓝色 (17)	PA (20.69)		1700~5000 (16.2)	[35]	
					PET (17.24)				
				黑色 (36.6)	PET (42.3)				
反硝化-超滤-臭氧-紫外线消毒	2.21±1.43	0.59±0.22	—	透明 (33.84)	PES (19.1)	纤维 (85.9)	<1000 (64.2)	[36]	
				蓝色 (11.88)	PP (13.1)		1000~2000 (28.7)		

续表 1

水厂类型	国家	处理工艺	工艺进水丰度 (个/L)	工艺出水丰度 (个/L)	颜色	成分	形状	粒径(μm)	文献
污水处理厂	韩国	快速砂滤-紫外线 消毒	1	0.5	—	丙烯酸 (25.2)	碎片 (55.7) 纤维 (44.3)	20~50 (36.0)	[37]
						PP (24.3)		50~200 (33.8)	
		臭氧	164	33	—	—	颗粒 (78.9) 纤维 (12)	—	[38]
	印度	纤维转盘过滤-氯 消毒	328	278	黑色 (76) 透明 (10.7) 其他 (13.3)	PE PP PS	碎片 (87.1) 纤维 (12.9)	<240 (75) 240~2090 (25)	[39]
饮用水厂	中国	紫外线消毒	386±211	377±23	—	PP (24.4)	碎片 (81.5) 纤维 (18.5)	1~5 (84.0)	[40]
						PET (19.0)		5~10 (12.2)	
		臭氧	2230±104	2348±109	—	PET (30.2) PE (23.3) PP (14.5) PAM (10.8)	纤维 (52.2) 碎片 (29.8)	1~5 (85.0) 5~10 (14.0) 10~50 (1.0)	[23]
		氯消毒	963±57	936±51	—	PET (53.8) PE (12.9) PP (12.7) PAM (12.6)	纤维 (67.1) 碎片 (26.2)	1~5 (87.0) 5~10 (13.5)	
	捷克共和国	臭氧	243±17	224±3	—	醋酸纤维素 (27.8)	碎片 (77.5) 纤维 (12.5)	1~5 (48.9) 5~10 (33.1) 10~50 (12.0) >50 (6.0)	[41]
		紫外线-氯消毒	149±1	151±4	—	醋酸纤维素 (25.1)	碎片 (78.7) 纤维 (11.3)	1~5 (50.2) 5~10 (33.0) 10~50 (8.2) >50 (8.6)	
饮用水厂	西班牙	氯消毒	0.06±0.04	0.06±0.04	—	PES (41.6)	纤维 (54.6) 碎片 (45.4)	20~200 (14.0)	[42]
						PP (37.7)		200~500 (42.3)	
		电渗析-氯消毒	0.032±0.013	0.075±0.019	—	人造纤维素 (53)	碎片 (53) 纤维 (37)	50~100 (33.0)	[43]
		氯消毒	578	521±61	—	PE (16) PP (5)	薄膜 (11)	100~500 (67.0)	
	柬埔寨	氯消毒	693	617±147	—	PET (28.8) PE (27.1) PP (8.5) PES/PA (6.8)	碎片 (60.8) 纤维 (39.2)	6.5~20 (36.5) 20~53 (32.4) 53~500 (19.8) >500 (11.3)	[44]
		氯消毒	693	617±147	—	PET (26) PE (20.8) PA (10.4) PES (9.1)	碎片 (53.4) 纤维 (46.6)	6.5~20 (42.0) 20~53 (29.0) 53~500 (19.9) >500 (9.1)	[44]
	印度	预氯化消毒	17.88	17.53	—	PET (56) PE (33)	纤维 (55) 碎片/薄膜 (45)	<25 (29.9) 25~50 (16.9) 50~100 (50.3) >100 (2.8)	[45]

续表 1

水厂类型	国家	处理工艺	工艺进水丰度 (个/L)	工艺出水丰度 (个/L)	颜色	成分	形状	粒径(μm)	文献
饮用水厂	印度尼西亚	氯消毒	13.8	12.3	黑色 (50.4)	PES PE PP	纤维 (92.8) 碎片 (7.2)	1~100 (14.5)	[46]
					黄色 (18.7)			101~350 (25.4)	
					红色 (16.3)			351~1000 (39.9)	
					蓝色 (14.6)			1001~5000 (20.3)	
		氯消毒	29.7	8.5	黑色 (38.8)	PES PE PP	纤维 (96) 碎片 (4)	1~100 (10.4)	[46]
					蓝色 (27.1)			101~350 (20.2)	
					红色 (12.2)			351~1000 (38.4)	
					黄色 (15.3)			1001~5000 (31.0)	

注:1)颜色、成分、形状、粒径列括号中的数值单位均为%;2)“—”表示文献中未提及该信息。

PET 常用于制造服装纤维、塑料瓶和相机胶片。PE 是全球产量最大的塑料^[15],主要应用于食品包装膜和塑料袋等。PP 则用于制造塑料容器、纺织品、食品包装和管道^[16],并在水环境中易氧化分解成小颗粒^[17]。据报道,污水处理厂中 PET、PE 和 PP 可能源自洗涤纤维材料产生的废水^[18-19]。由于 PE 和 PP 的密度比水低,它们能够通过水流进行长距离迁移,从而威胁到饮用水水源^[20]。PS 在许多轻工业中都有使用,如日常装饰、照明设备和包装^[21]。PA(尼龙)作为一种常见的塑料材料,可能来源于各种形式的纺织品^[22]。值得注意的是,在一所饮用水厂消毒过程中,检测到了较高含量的聚丙烯酰胺(PAM),而原水中并未含有^[23]。这与使用含 PAM 的混凝剂有关,进而导致后续工艺和水质受到该物质污染。已有研究表明,PAM 不仅会对生物体造成影响,而且在消毒的氧化作用下,能加速降解成各种低聚物以及剧毒的丙烯酰胺单体。丙烯酰胺单体通过饮用水进入人体后,可能引发平衡紊乱、嗜睡、幻觉和记忆丧失等症状^[24],对人类健康构成严重威胁。因此,在利用 PAM 处理饮用水的地区,有必要对其用量进行评估。

1.2 MPs 形状

MPs 在消毒工艺中呈现有纤维状、碎片状、薄膜状和颗粒状等多种形态,如表 1 所示,污水消毒中,纤维状 MPs 占总 MPs 数量的 12%~100%,且成分主要为 PET 和 PP。当洗涤相关合成纤维制成的衣物时,会释放大量的 MPs 纤维,并随着洗衣废水进入污水处理厂^[25];研究估算,平均 6kg 的腈纶织物洗涤量可以释放出超过 70 万根 MPs 纤维^[26]。Xu 等^[27]研究结果显示,常州市 11 座污水处理厂中纤维是污水中 MPs 的主要形状,在进水和出水中占比分别为 88.69%和 86.66%。齐杰等^[28]发现,邯郸市某污水厂两

期工程中纤维状 MPs 占比最高,是污水厂最难以处理、消毒后排放最多的 MPs。其次是碎片/薄膜,消毒工艺中碎片/薄膜占比最高可达 87.1%。Zhang 等^[29]报道了贵阳某三级污水处理厂中碎片/薄膜状 MPs 经过消毒处理后仍占较高比例。这些 MPs 可能来源于日常使用的塑料制品降解形成。颗粒状 MPs 则通常来源于个人护理和化妆品中的微珠。此前的一份报告估计,全球个人护理产品中的塑料微珠排放量可达 $1.2 \times 10^4 \text{ t/a}$ ^[30]。但自 2015 年,一项禁止塑料微珠的提案得到了公开支持^[31],不少国家陆续开始禁止生产含有塑料微珠的日化品,因而大部分污水处理厂及其消毒中未观察到颗粒状 MPs 的存在。此外,饮用水消毒中的 MPs 也以纤维状和碎片状为主,这表明饮用水处理工艺中仍难以完全去除这类 MPs。

1.3 MPs 粒径

在污水处理厂和饮用水厂的有关报道中,MPs 粒径的下限随不同收集和检测手段而不同,MPs 粒径下限越小,纳入研究的粒径范围越广,MPs 的总数越多。而且不同研究对 MPs 粒径范围的划分存在差异,进而对粒径大小的判定不尽相同,公认最小粒径为 $1 \mu\text{m}$ ^[47]。大体来看(表 1),在消毒工艺中较小粒径($<500 \mu\text{m}$)的 MPs 占比最多,大粒径 MPs($>1000 \mu\text{m}$)丰度相对较低。这可能是由于较小的 MPs 通常比较大的塑料颗粒更难去除^[45-46];同时,大粒径 MPs 在处理过程中能被破碎成更小的 MPs^[50]。Wu 等^[51]研究表明,释放到水生环境中的小粒径 MPs($75 \mu\text{m}$)更容易被生物膜定殖,并与生物膜形成异质聚集体,进而能吸附更多重金属,增加了生态风险。Yan 等^[52]指出在氯化过程中较小粒径的 MPs 会导致更多的 DOM 浸出。对于粒径 $<1 \mu\text{m}$ 的纳米塑料,其具有更强的反应性和吸附能力^[53]。然而,目前在水厂中对纳

米塑料的丰度和特征研究还相对较少.在已有的报道中^[54],以松花江为原水的某饮用水厂,消毒处理前后纳米塑料浓度分别为 0.08 和 0.04 $\mu\text{g}/\text{L}$.Li 等^[55]发现饮用水厂进水中 PE 和 PVC 纳米塑料(20~1000nm)的浓度分别为 0.86 和 137.31 $\mu\text{g}/\text{L}$,在臭氧处理单元出水中分别提高至 4.49 和 208.64 $\mu\text{g}/\text{L}$.其中可能的原因是 PE 和 PVC 塑料管道的老化导致纳米塑料增加^[56].

1.4 MPs 颜色

国内外部分水厂消毒工艺中,MPs 的颜色主要以黑色和透明为主,黄色、红色和蓝色等占比较低(表 1).这可能与人们日常生活中对黑色和透明塑料制品的高消费量有关^[32].而且长时间浸泡在水中的彩色 MPs 会被氧化和老化,逐渐变为透明或黑色^[57].

总体来看,MPs 在污水处理厂和饮用水厂消毒中的特征相似,尽管前期处理工艺能去除大部分 MPs,但对于无法通过常规工艺去除的 MPs,其在消毒中的去除效果及其潜在风险需要深入分析.

2 不同消毒工艺对 MPs 的去除效果分析

目前,MPs 在水处理消毒中的去除机制尚不清楚,其中的氧化作用能加速老化和降解,但消毒工艺对 MPs 的氧化降解能否产生去除效果,需要进一步分析.

2.1 氯消毒

氯消毒是使用最为广泛的消毒方法,氯化过程形成的次氯酸具有强氧化性.氯化 MPs 有两种反应途径:一方面,次氯酸会分解形成氧分子,导致 MPs 氧化^[58],另一方面,次氯酸会产生具有反应性的 HO·和 Cl·,它们能与 MPs 发生反应,并在 MPs 表面形成羰基,使 MPs 也能进行自氧化^[59].并且经过长时间接触可能会导致塑料键的断裂,形成碳氯键,这一过程中 MPs 发生降解^[60].在水厂中,氯消毒的浓度、接触时间、水质条件和 MPs 特征都会影响 MPs 的去除效果^[61].Liu 等^[22]研究发现,氯消毒对 MPs 的去除率仍有 7.1%.Galafassi 等^[62]也报道了在意大利的 4 个中小型污水处理厂中,使用次氯酸钠消毒对 MPs 的去除率为 15.8%~67.6%.然而,在符合污水处理厂和饮用水厂消毒的氯浓度下,观察粒径 100~200 μm 的 PE 和 PS 在其中持续 14d,仍不足以对 MPs 产生明显氧化降解反应,羰基指数仅为 0.0252 和

0.2900^[63].氯消毒对 MPs 的去除效果则可能更多地归因于消毒池的沉淀作用^[64].总体而言,尽管氯消毒对 MPs 的去除有一定效果,但其去除率受多种因素影响,且在标准氯消毒条件下,MPs 的氧化降解并不显著.

2.2 臭氧消毒

臭氧可以通过臭氧分子和臭氧分解生成的活性氧自由基进行氧化 MPs,使其化学结构发生改变,形成羟基(O-H)和羰基(C=O)等官能团,从而引发 MPs 的降解过程.对于尺寸较大的塑料制品,Zhang 等^[65]研究发现臭氧能氧化给水塑料管材,使其表面产生裂纹并碎裂释放 MPs.对于尺寸小至纳米级的塑料,Li 等^[66]报道,在臭氧平均用量为 4.1mg/L 时,纳米级 PS 在 30min 内达到了 96.3%的相对分子质量降解,矿化度降低了 42.7%.随着臭氧处理的进行,塑料表面变得粗糙,亲水性提高且粒径进一步减小.目前,臭氧氧化塑料的能力已得到充分报道,但对其在污水处理厂和饮用水厂中处理 MPs 的有效性尚未达成一致.Hidayaturrahman 等^[38]研究了在韩国 3 种不同三级处理中 MPs 的去除率,发现与膜盘式过滤和快速砂滤相比,臭氧氧化工艺对 MPs 的去除效果更为显著,在臭氧平均用量为 12.6mg/L 时去除率达 89.9%.Wang 等^[23]研究结果表明,在最高采用 2.5mg/L 臭氧处理后,出水中 MPs 数量甚至增加了 2.8%~16.0%,导致了臭氧工艺的负去除率,这可能是由于 MPs 在水流剪切力的作用下破碎所致^[67].Pivokonsky 等^[41]报道了饮用水厂中的臭氧处理使 MPs 丰度从(243 \pm 17)个/L 去除到(224 \pm 3)个/L,去除率仅为 7.8%.这些结果显示,臭氧处理在不同水处理系统中的实际应用效果存在差异,尽管去除 MPs 的原因可能不完全是氧化作用,还是有必要采用相应的实际臭氧用量和暴露时间对 MPs 进行更多的研究,进一步证实臭氧处理的影响,并阐明去除 MPs 的确切机制.

2.3 紫外线消毒

MPs 受紫外线照射后,其表面的 O-H、C=O、过氧化氢基(ROOH)和 C=C 双键会形成含氧自由基并产生一系列连锁反应,导致其开始出现裂缝、断裂、破碎^[68].然而,现有多数研究中所用紫外线剂量和持续时间均超过水厂的通常使用水平(约 20~3000mJ/cm²).并且在水厂实际应用中,紫外线消毒对

MPs 的去除效果仍存争议.一些研究表明,紫外线消毒会导致水中的 MPs 丰度增加^[35,19].而 Galafassi 等^[62]的研究发现,污水处理厂的紫外线消毒对 MPs 的去除率为 9.1%.Jiang 等^[34]也研究发现中国哈尔滨的一污水处理厂中紫外线消毒对 MPs 有一定的去除效果,其研究中 MPs 丰度从(37.9±8.5)个/L 减少至(30.6±7.8)个/L.但 Lin 等^[69]采用了 3720mJ/cm² 的紫外线剂量模拟污水处理厂中紫外线照射平均粒径为 780μmPS-MPs 的极端情况,结果表明,紫外线照射对 MPs 的形状和尺寸影响不大.Liu 等^[64]也得到了类似的结论.对此,实际紫外线消毒中 MPs 可能并不会被氧化降解掉,进而达到去除效果,MPs 的去除机制有待进一步去探索.

综上所述,常见消毒工艺对 MPs 的去除效果具有显著差异,尤其在部分水厂的臭氧消毒和紫外线消毒后,MPs 丰度反而上升.消毒工艺能提升 MPs 的下沉率^[64],该作用对去除率的影响可能是不可忽视.根据表 1 中 MPs 的进、出水丰度,得到氯消毒单元去除率在 0~71.38%、臭氧在-5.29%~79.88%、紫外线消毒在-56.76%~19.26%.

3 消毒工艺中 MPs 的潜在风险

3.1 MPs 对消毒效果的影响

MPs 的存在会较大程度的干扰消毒过程,对消毒工艺产生负向影响,主要表现为微生物灭活效果降低以及病原体和抗性基因传播风险的增加^[70-71].随着公共卫生事件的频繁发生,水厂消毒成为减少病原体传播的重要手段.然而,残留在消毒工艺中的 MPs 成为病原体和抗性基因的庇护所(图 1);当有效氯含量为 0.45mmol/L,MPs 浓度达到 5mg/L 时,经过 30min 后也不能满足灭菌要求,水中仍有超过 10CFU/mL 的大肠杆菌^[72].Nguyen 等^[73]报道了在污水处理厂出水的 MPs 表面发现了 16 种致病细菌、抗生素抗性菌(ARB)以及抗生素抗性基因(ARGs),并在饮用水厂出水中的 MPs 表面仍发现了 9 种潜在的致病细菌、ARB 和 ARGs,包括假单胞菌、不动杆菌和弧菌等,对公共健康构成了潜在威胁.

3.1.1 消毒中 MPs 对灭活微生物的影响 氯消毒中次氯酸的强氧化性,能杀灭水中病原微生物.但水中 MPs 的存在,作为微生物的附着基质,阻碍氯对微生物的作用,从而使氯的消毒效率降低^[74].Shen 等^[72]

研究发现 MPs 的存在显著降低了水处理中紫外线消毒和氯消毒的效率,且随着 MPs 浓度的增加或消毒剂浓度的减少而降低;当 PE-MPs 浓度达到特定水平(>50mg/L)时,即使进一步增加有效氯含量和消毒时间,MPs 表面的大肠杆菌仍能进行复活.Tang 等^[75]研究了 PE-MPs 对次氯酸钠消毒的影响,溶液中的 PE-MPs 能在 30s 内与 1.5log₁₀ 大肠杆菌发生作用,并保护其免受水环境因素的影响,使灭活率显著降低.

臭氧与氯同样作为强氧化剂,但它能通过攻击细胞膜来杀死耐氯微生物^[76].尽管如此,MPs 也能通过与臭氧发生反应,降低臭氧的浓度,从而减少对细菌的杀灭能力^[8].Adeel 等^[77]也证实了这一结论,其研究结果显示臭氧的消毒效率随着 MPs 浓度(范围在 0.25~1.0g/L)的增加而降低.相关研究表明,MPs 能消耗臭氧产生的自由基^[78],并在表面留下裂缝和沟槽,这可能会促进微生物更好地附着在 MPs 表面,保护其不被灭活^[79].

紫外线消毒是利用短波长紫外线破坏病原微生物的 DNA 或 RNA 结构来实现灭菌.但作为悬浮颗粒物的 MPs 在水中能通过散射/阻挡紫外线,并与病原体聚合来对灭菌效果产生负面影响^[13].而且紫外线辐射达到一定剂量后,即使继续增加消毒时间,灭菌效果也没有明显提高^[72].Manoli 等^[80]研究表明,在较高紫外线剂量下 MPs 的存在会使细菌具有更慢的灭活速度或无灭活,且不同 MPs 对消毒的负向影响程度各不相同.此外,在探究 MPs 对紫外/过氧化氢(UV/H₂O₂)的影响中发现,有 MPs 情况下该体系的消毒效率反而不如仅紫外线消毒,但对大肠杆菌的灭活率随着 H₂O₂ 浓度的增加而提升^[77].

与 UV/H₂O₂ 相比,太阳光驱动的高级氧化具有节能环保优势,被认为是小型污水处理厂进行污水消毒的有效且可持续的解决方案.其中太阳光/H₂O₂ 的消毒效率也是会随着 MPs 初始浓度的增加而降低.相反,MPs 对太阳光-芬顿消毒有正向影响,大肠杆菌灭活率随着 MPs 浓度的增大而上升^[81];这可能是 MPs 促进活性氧的形成.综上,MPs 在常见的消毒工艺中具有负向影响,但在高级氧化以及组合消毒工艺中的影响及其机制仍待进一步研究.

3.1.2 消毒中 MPs 对去除抗性基因的影响 消毒过程中,微生物死亡会导致抗性基因以游离 DNA 的

形式释放到细胞外.研究表明,随着氯和紫外线剂量的增加,ARGs 的丰度显著降低^[82];但在臭氧浓度为 2mg/L 时,磺胺类和四环素类 ARGs 的去除率分别为 34.5%和 49.2%,进一步提高臭氧浓度并未显著改善去除效果.当 MPs 存在时,Galafassi 等^[83]发现臭氧消毒对 MPs 上的抗生素和金属抗性基因丰度已无显著影响.Yang 等^[84]报道,PS-MPs 通过提供定殖场所和增加水体浑浊度,影响紫外线消毒中的 ARGs 种

类和丰度,不同粒径的 PS-MPs 在一定浓度下均会增加 ARGs 的含量.而且紫外线老化的 MPs 具有更强的吸附能力^[85],进一步增加 ARGs 在 MPs 生态电晕中的丰度^[86].Huang 等^[87]的研究表明,在 8mg/L Cl₂ 作用 20min 的条件下,PE-MPs 的存在使 ARGs 的降解效率降低了 11.1~18.6 个百分点.因此,MPs 的存在会降低消毒工艺对抗性基因的去效率,进而促进这些基因在水生环境中的传播.

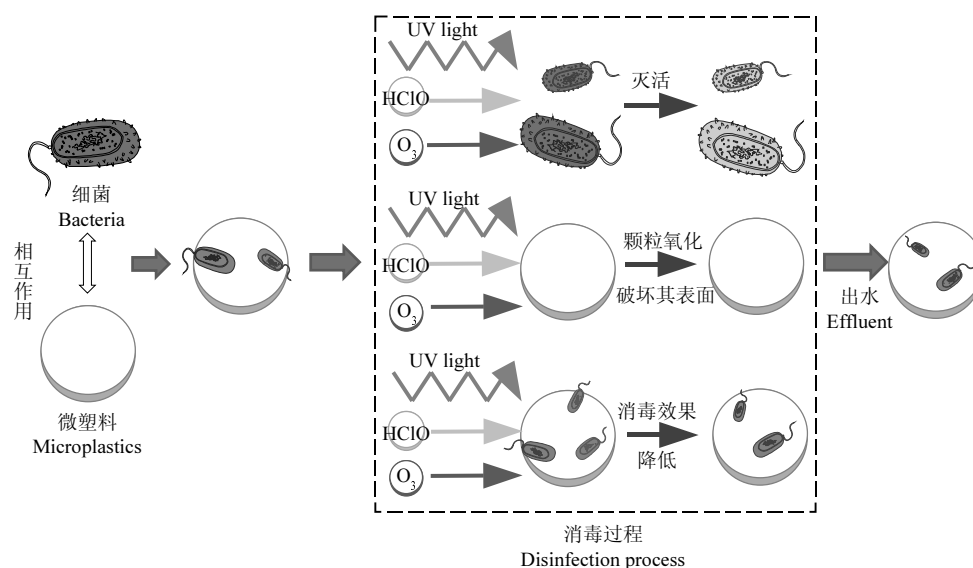


图 1 消毒过程中 MPs 的氧化和保护微生物的作用机制^[56,59]

Fig.1 The mechanisms of oxidation by MPs and the protective effects on microorganisms during the disinfection process

3.2 消毒工艺中 MPs 的二次污染

MPs 在水中会释放 DOM,即 MPs 溶解性有机物 (MP-DOM),其释放量全球每年超过 2.36 万 t^[14].有报道称,紫外线照射 14d 后,PU-MPs 的溶解有机碳 (DOC)累积速度是黑暗条件下的 9 倍^[88],发泡聚苯乙烯塑料(EPS)则比在黑暗条件下的 DOC 浓度高 80 多倍^[89].同样,Lee 等^[90]也报道了紫外线照射能促进 MP-DOM 的浸出,浸出量相当于塑料聚合物总质量的 3%左右.Lin 等^[91]发现氯化作用可以促进 MPs 对有机物的浸出,总浸出 DOC 占 MPs 总质量的 0.3%~0.5%;且在氯化过程中,PS 比 PE 更易浸出有机物.这些 MP-DOM 可能包含多种有机化合物,从邻苯二甲酸盐、双酚、多氯联苯和溴化阻燃剂到多环芳烃、杀虫剂和药物^[92],对生物体和人类产生不同的影响^[93].Ouyang 等^[94]研究了 PVC 在 3 种不同紫外线波长下的老化过程,用大肠杆菌检测降解的 MPs 中间产物的毒性,结果发现,在 UV254nm 照射下,MPs 浸

出物产生毒性均大于 UV320-400nm 和 UV280-320nm 照射下的结果.Du 等^[95]指出 PA 和 PET 浸出的 DOM 对费氏弧菌活性有抑制作用;并且使用小球藻和铜绿微囊藻进行的生物测定表明,MP-DOM 可通过破坏细胞膜的通透性和完整性来抑制微藻的生长.Xu 等^[88]进行了对人结肠癌细胞的毒性测试,研究发现 PU 释放的 DOM 确实产生了毒性,导致细胞存活率降低和膜损伤.由此而言,MP-DOM 在消毒过程中的加速浸出,可能对生态系统和人类健康造成影响,未来需要全面评估其毒性和风险水平.

为了抑制水厂出水中残余微生物的复活和再度繁殖,通常需要加氯处理.然而,在氯化处理过程中,DOM 与氯反应形成有毒的消毒副产物是不可避免的结果,并且可以说,这是 DOM 对水生生态系统和人类健康的最关键风险之一.Yan 等^[52]研究结果表明,MP-DOM 可作为消毒副产物的前驱体,主要生成三氯甲烷,生成的潜能分别为(60.3±7.8)和(73.7±

9.8) $\mu\text{g}/\text{mg}$ 。而且随着 PS-MPs 粒径从 50 μm 减小至 5 μm ,其对三氯甲烷的吸附能力增加了 2.7 倍,从而进一步增大了 MPs 的潜在风险。此外,将 MP-DOM 生成消毒副产物三卤甲烷的潜能(THMFP)与典型的水生天然有机物(NOM)、藻类有机物(AOM)在类似的氯化条件下进行对比,如表 2 所示。结果显示,无论来自湖泊或是地下水的 NOM、还是来自 AOM,MP-DOM 生成三卤甲烷的潜力是相当甚至更大的^[90],即 MP-DOM 会带来更大的健康风险。

表 2 MP-DOM 与典型水生 NOM、AOM 氯化生成的 THMFP 值比较

Table 2 Comparison of THMFP values generated by chlorination of MP-DOM with typical aquatic NOM and AOM

有机物种类	来源	反应时间(d)	温度($^{\circ}\text{C}$)	THMFP($\mu\text{g}^{-1}\text{THM}/\text{mg}^{-1}\text{C}$)	文献
MP-DOM	PP	7	25	81.1-82.1	[96]
	PS	7	25	76.8-82.3	[96]
	PE	4	25	80.48 \pm 4.53	[91]
	PS	4	25	125.48 \pm 8.90	[91]
	EPS 和 PVC(原始)	3	25	110.05 \pm 9.05	[97]
	EPS 和 PVC(老化)	3	25	135.6 \pm 13.4	[97]
	PE 和 PP(黑暗)	3	25	1.9-109.6	[90]
PE 和 PP(光照)	3	25	29.2-453.3	[90]	
NOM	地下水	1	25	47.1	[98]
	湖岸滤液	7	25 \pm 2	54.2 \pm 16.0	[99]
AOM	小球藻	7	25	10.1-12.1	[100]
	微囊藻	7	20	42.6 \pm 3.3	[101]

注:THMFP值是将测定的消毒副产物除以相应的DOC。

在多级消毒工艺中,如水厂采用臭氧预氧化或紫外线消毒后再加氯处理时,MPs 在臭氧氧化过程中虽然不会显著增加 MP-DOM 的释放量,但会改变其特征(如分子量减小),从而增强 MPs 与氯的反应活性,显著增加卤代乙酸(如二氯乙酸)和卤代乙醛(如三氯乙醛)等消毒副产物的生成量,最高增加 34 倍^[102]。UV/氯的过程中,MPs 在紫外线照射下浸出的 DOM 也极有可能生成消毒副产物。因此,MPs 在消毒过程中可能产生一些不确定且毒性更强的物质,尤其在饮用水处理中应用紫外线或臭氧消毒时,潜在风险不可忽视。

4 结语

MPs 在水处理消毒中主要以纤维、碎片形状存

在,以 PET、PE 和 PP 为主,粒径大部分小于 1.0mm,颜色多呈黑白和透明,其进水丰度为 0.01~2230 个/L,出水丰度为 0.13~2348 个/L。水厂中氯消毒在短时间内不足以氧化降解来去除 MPs,而部分紫外线和臭氧消毒工艺中 MPs 丰度反而上升。由于 MPs 的去除率受诸多因素影响,其去除机制和影响因素尚需进一步研究。MPs 在水消毒中能消耗氧化剂、阻挡紫外线,并与微生物快速相互作用,随着 MPs 浓度的增加,消毒效果会随之降低。此外,MPs 在氯和紫外线氧化下会释放更多 MP-DOM,其具有较强生成消毒副产物的潜能,而形成的这些副产物对人类健康和生态环境的威胁比原来 MPs 更大。目前,对于小粒径 MPs 的去除以及在水消毒工艺中对微生物的影响和产生的二次污染物的相关研究仍存在一定的局限性和不足,主要有以下 3 点建议:

(1)改进常规水处理工艺,增强混凝、沉降和过滤效果;开发新型水处理技术,如新型吸附材料和膜技术。还可结合多道工序,来有效控制小粒径 MPs,特别是纤维状和碎片状 MPs,防止其大量进入消毒工艺。

(2)开展 MPs 对高级氧化和组合消毒工艺的影响及其机制研究。高级氧化和组合消毒工艺的强氧化性可能对 MPs 的结构、形态以及与微生物的相互作用产生独特的影响,探明不同消毒过程中 MPs 对微生物的影响作用,对优化消毒工艺提供理论依据。

(3)结合生物毒理学实验和化学模拟,评估消毒后 MPs 以及所形成二次污染物的毒性,确定 MPs 生态安全和健康风险的阈值浓度,以保证出水水质安全。

参考文献:

- [1] Cao Y, Lin H, Zhang K, et al. Microplastics: A major source of phthalate esters in aquatic environments [J]. *Journal of Hazardous Materials*, 2022,432:128731.
- [2] 何艺欣,唐炳然,张丽雪,等.老化聚苯乙烯纳米塑料对铜绿微囊藻的影响 [J]. *中国环境科学*, 2022,42(12):5877-5884.
He Y X, Tang B, Zhang L X, et al. Effects of aged polystyrene nanoplastics to *Microcystis aeruginosa* [J]. *China Environmental Science*, 2022,42(12):5877-5884.
- [3] 徐成龙,吴培,陈波,等.二类生物可降解塑料对铜绿微囊藻的毒性效应 [J]. *中国环境科学*, 2024,44(11):6495-6503.
Xu C L, Wu P, Chen B, et al. Toxic effects of class II biodegradable plastics on *Microcystis aeruginosa* [J]. *China Environmental Science*, 2024,44(11):6495-6503.
- [4] Qiao R, Sheng C, Lu Y, et al. Microplastics induce intestinal

- inflammation, oxidative stress, and disorders of metabolome and microbiome in zebrafish [J]. *Science of the Total Environment*, 2019, 662:246–253.
- [5] K c P B, Maharjan A, Acharya M, et al. Polytetrafluorethylene microplastic particles mediated oxidative stress, inflammation, and intracellular signaling pathway alteration in human derived cell lines [J]. *Science of the Total Environment*, 2023,897:165295.
- [6] Chen Z, Liu X, Wei W, et al. Removal of microplastics and nanoplastics from urban waters: Separation and degradation [J]. *Water Research*, 2022,221:118820.
- [7] 柴怡然,徐慧捷,高柯玄,等.微塑料在水处理工艺中的分离去除及研究进展 [J]. *环境科学*, 2024,45(10):6112–6128.
- Chai Y R, Xu H J, Gao K X, et al. Advances in the separation and removal of microplastics in water treatment processes [J]. *Environmental Science*, 2024,45(10):6112–6128.
- [8] Enfrin M, Dumée L F, Lee J. Nano/microplastics in water and wastewater treatment processes – Origin, impact and potential solutions [J]. *Water Research*, 2019,161:621–638.
- [9] Leslie H A, Brandsma S H, van Velzen M J M, et al. Microplastics en route: Field measurements in the Dutch river delta and Amsterdam canals, wastewater treatment plants, North Sea sediments and biota [J]. *Environment International*, 2017,101:133–142.
- [10] Liu L, Xu M, Ye Y, et al. On the degradation of (micro)plastics: Degradation methods, influencing factors, environmental impacts [J]. *Science of the Total Environment*, 2022,806:151312.
- [11] Li Y, Liu C, Yang H, et al. Leaching of chemicals from microplastics: A review of chemical types, leaching mechanisms and influencing factors [J]. *Science of the Total Environment*, 2024,906:167666.
- [12] Ding S, Deng Y, Bond T, et al. Disinfection byproduct formation during drinking water treatment and distribution: A review of unintended effects of engineering agents and materials [J]. *Water Research*, 2019,160:313–329.
- [13] Chahal C, van den Akker B, Young F, et al. Chapter two – Pathogen and particle associations in wastewater: Significance and implications for treatment and disinfection processes [M]/SARIASLANI S, MICHAEL GADD G. *Advances in Applied Microbiology: Vol. 97*. Academic Press, 2016:63–119.
- [14] Liu S, Qiu Y, He Z, et al. Microplastic-derived dissolved organic matter and its biogeochemical behaviors in aquatic environments: A review [J]. *Critical Reviews in Environmental Science and Technology*, 2024,54(11):865–882.
- [15] Kang H J, Park H J, Kwon O K, et al. Occurrence of microplastics in municipal sewage treatment plants: a review [J]. *Environmental Health and Toxicology*, 2018,33(3):e2018013.
- [16] Zhu L, Bai H, Chen B, et al. Microplastic pollution in North Yellow Sea, China: Observations on occurrence, distribution and identification [J]. *Science of the Total Environment*, 2018,636:20–29.
- [17] Huang Y, Yan M, Xu K, et al. Distribution characteristics of microplastics in Zhubi Reef from South China Sea [J]. *Environmental Pollution*, 2019,255:113133.
- [18] De Falco F, Gullo M P, Gentile G, et al. Evaluation of microplastic release caused by textile washing processes of synthetic fabrics [J]. *Environmental Pollution*, 2018,236:916–925.
- [19] Lv X, Dong Q, Zuo Z, et al. Microplastics in a municipal wastewater treatment plant: Fate, dynamic distribution, removal efficiencies, and control strategies [J]. *Journal of Cleaner Production*, 2019,225:579–586.
- [20] Wang W, Yuan W, Chen Y, et al. Microplastics in surface waters of Dongting Lake and Hong Lake, China [J]. *Science of the Total Environment*, 2018,633:539–545.
- [21] Wen X, Du C, Xu P, et al. Microplastic pollution in surface sediments of urban water areas in Changsha, China: Abundance, composition, surface textures [J]. *Marine Pollution Bulletin*, 2018,136:414–423.
- [22] Liu X, Yuan W, Di M, et al. Transfer and fate of microplastics during the conventional activated sludge process in one wastewater treatment plant of China [J]. *Chemical Engineering Journal*, 2019,362:176–182.
- [23] Wang Z, Lin T, Chen W. Occurrence and removal of microplastics in an advanced drinking water treatment plant (ADWTP) [J]. *Science of the Total Environment*, 2020,700:134520.
- [24] 张学佳,纪巍,王宝辉,等.丙烯酸酰胺生态毒理行为研究进展 [J]. *生态毒理学报*, 2008,(3):217–223.
- Zhang X J, Ji W, Wang B H, et al. Progress in the research on ecotoxicological behavior of acrylamide [J]. *Asian Journal of Ecotoxicology*, 2008,(3):217–223.
- [25] 许霞,侯青桐,薛银刚,等.污水厂中微塑料的污染及迁移特征研究进展 [J]. *中国环境科学*, 2018,38(11):4393–4400.
- XU X, Hou Q T, Xue Y G, et al. Research progress on the transference and pollution characteristics of microplastics in wastewater treatment plants [J]. *China Environmental Science*, 2018,38(11):4393–4400.
- [26] Napper I E, Thompson R C. Release of synthetic microplastic plastic fibres from domestic washing machines: Effects of fabric type and washing conditions [J]. *Marine Pollution Bulletin*, 2016,112(1):39–45.
- [27] Xu X, Jian Y, Xue Y, et al. Microplastics in the wastewater treatment plants (WWTPs): Occurrence and removal [J]. *Chemosphere*, 2019,235:1089–1096.
- [28] 齐杰,王伟,刘旭光,等.传统氧化沟工艺城市污水厂微塑料形态、分布及去除 [J]. *中国环境科学*, 2024,44(11):6156–6163.
- Qi J, Wang W, Liu X G, et al. Morphology, distribution and removal of microplastics in municipal wastewater plants by traditional oxidation ditch technology [J]. *China Environmental Science*, 2024,44(11): 6156–6163.
- [29] Zhang B, Wu Q, Gao S, et al. Distribution and removal mechanism of microplastics in urban wastewater plants systems via different processes [J]. *Environmental Pollution*, 2023,320:121076.
- [30] Singh A, Mishra B K. Microbeads in personal care products: An overlooked environmental concern [J]. *Journal of Cleaner Production*, 2023,427:139082.
- [31] Rochman C M, Kross S M, Armstrong J B, et al. Scientific evidence supports a ban on microbeads [J]. *Environmental Science & Technology*, 2015,49(18):10759–10761.
- [32] Yang Z, Li S, Ma S, et al. Characteristics and removal efficiency of microplastics in sewage treatment plant of Xi'an City, northwest China [J]. *Science of the Total Environment*, 2021,771:145377.
- [33] Long Y, Zhou Z, Yin L, et al. Microplastics removal and characteristics of constructed wetlands WWTPs in rural area of Changsha, China: A different situation from urban WWTPs [J].

- Science of the Total Environment, 2022,811:152352.
- [34] Jiang J, Wang X, Ren H, et al. Investigation and fate of microplastics in wastewater and sludge filter cake from a wastewater treatment plant in China [J]. *Science of the Total Environment*, 2020,746:141378.
- [35] Ren P, Dou M, Wang C, et al. Abundance and removal characteristics of microplastics at a wastewater treatment plant in Zhengzhou [J]. *Environmental Science and Pollution Research*, 2020,27(29):36295–36305.
- [36] Yang L, Li K, Cui S, et al. Removal of microplastics in municipal sewage from China's largest water reclamation plant [J]. *Water Research*, 2019,155:175–181.
- [37] Kim M J, Na S H, Batool R, et al. Seasonal variation and spatial distribution of microplastics in tertiary wastewater treatment plant in South Korea [J]. *Journal of Hazardous Materials*, 2022,438:129474.
- [38] Hidayaturrehman H, Lee T G. A study on characteristics of microplastic in wastewater of South Korea: Identification, quantification, and fate of microplastics during treatment process [J]. *Marine Pollution Bulletin*, 2019,146:696–702.
- [39] Patil S, Kamdi P, Chakraborty S, et al. Characterization and removal of microplastics in a sewage treatment plant from urban Nagpur, India [J]. *Environmental Monitoring and Assessment*, 2022,195(1):47.
- [40] 闵 芮,周添红,张洪伟,等.黄河上游给水厂中微塑料的出现及去除效率 [J]. *中国环境科学*, 2024,44(5):2672–2679.
- Min R, Zhou T H, Zhang H W, et al. Occurrence and removal efficiency of microplastics in the upper Yellow River water supply plants [J]. *China Environmental Science*, 2024,44(5):2672–2679.
- [41] Pivokonský M, Pivokonská L, Novotná K, et al. Occurrence and fate of microplastics at two different drinking water treatment plants within a river catchment [J]. *Science of the Total Environment*, 2020,741:140236.
- [42] Dalmau-Soler J, Ballesteros-Cano R, Boleda M R, et al. Microplastics from headwaters to tap water: occurrence and removal in a drinking water treatment plant in Barcelona Metropolitan area (Catalonia, NE Spain) [J]. *Environmental Science and Pollution Research*, 2021, 28(42):59462–59472.
- [43] Dronjak L, Exposito N, Rovira J, et al. Screening of microplastics in water and sludge lines of a drinking water treatment plant in Catalonia, Spain [J]. *Water Research*, 2022,225:119185.
- [44] Babel S, Dork H. Identification of micro-plastic contamination in drinking water treatment plants in Phnom Penh, Cambodia [J]. *Journal of Engineering and Technological Sciences*, 2021,53:210307.
- [45] Sarkar D J, Das Sarkar S, Das B K, et al. Microplastics removal efficiency of drinking water treatment plant with pulse clarifier [J]. *Journal of Hazardous Materials*, 2021,413:125347.
- [46] Radityaningrum A D, Trihadiningrum Y, Mar'atusholihah, et al. Microplastic contamination in water supply and the removal efficiencies of the treatment plants: A case of Surabaya City, Indonesia [J]. *Journal of Water Process Engineering*, 2021,43:102195.
- [47] Frias J P G L, Nash R. Microplastics: Finding a consensus on the definition [J]. *Marine Pollution Bulletin*, 2019,138:145–147.
- [48] Wang Z, Sedighi M, Lea-Langton A. Filtration of microplastic spheres by biochar: removal efficiency and immobilisation mechanisms [J]. *Water Research*, 2020,184:116165.
- [49] Sharma S, Basu S, Shetti N P, et al. Microplastics in the environment: Occurrence, perils, and eradication [J]. *Chemical Engineering Journal*, 2021,408:127317.
- [50] 陈 瑀,张 宴,苏良湖,等.南京市污水处理厂中微塑料的赋存特征 [J]. *中国环境科学*, 2020,40(9):3835–3841.
- Chen Y, Zhang Y, Su L H, et al. Occurrence characteristics of microplastics in Nanjing urban wastewater treatment plant [J]. *China Environmental Science*, 2020,40(9):3835–3841.
- [51] Wu C, Tanaka K, Tani Y, et al. Effect of particle size on the colonization of biofilms and the potential of biofilm-covered microplastics as metal carriers [J]. *Science of the Total Environment*, 2022,821:153265.
- [52] Yan Z, Qian H, Yao J, et al. Mechanistic insight into the role of typical microplastics in chlorination disinfection: Precursors and adsorbents of both MP-DOM and DBPs [J]. *Journal of Hazardous Materials*, 2024, 462:132716.
- [53] Sharma V K, Ma X, Lichtfouse E, et al. Nanoplastics are potentially more dangerous than microplastics [J]. *Environmental Chemistry Letters*, 2023,21(4):1933–1936.
- [54] Xu Y, Ou Q, Wang X, et al. Mass concentration and removal characteristics of microplastics and nanoplastics in a drinking water treatment plant [J]. *ACS ES&T Water*, 2024,4(8):3348–3358.
- [55] Li Y, Zhang C, Tian Z, et al. Identification and quantification of nanoplastics (20–1000nm) in a drinking water treatment plant using AFM-IR and Pyr-GC/MS [J]. *Journal of Hazardous Materials*, 2024,463:132933.
- [56] 郑莹莹,张可佳,岑 程,等.供水管网中微/纳米塑料的赋存及污染特性 [J]. *中国环境科学*, 2022,42(4):1610–1617.
- Zheng Y Y, Zhang K X, Cen C, et al. The abundance and contamination characteristics of micro/nano-plastics in drinking water distribution systems [J]. *China Environmental Science*, 2022,42(4): 1610–1617.
- [57] Tang N, Liu X, Xing W. Microplastics in wastewater treatment plants of Wuhan, Central China: Abundance, removal, and potential source in household wastewater [J]. *Science of the Total Environment*, 2020, 745:141026.
- [58] Mitroka S M, Smiley T D, Tanko J M, et al. Reaction mechanism for oxidation and degradation of high density polyethylene in chlorinated water [J]. *Polymer Degradation and Stability*, 2013,98(7):1369–1377.
- [59] Castillo Montes J, Cadoux D, Creus J, et al. Ageing of polyethylene at raised temperature in contact with chlorinated sanitary hot water. Part I –Chemical aspects [J]. *Polymer Degradation and Stability*, 2012, 97(2):149–157.
- [60] Castagnetti D, Scirè Mammano G, Dragoni E. Effect of chlorinated water on the oxidative resistance and the mechanical strength of polyethylene pipes [J]. *Polymer Testing*, 2011,30(3):277–285.
- [61] Acarer S. Abundance and characteristics of microplastics in drinking water treatment plants, distribution systems, water from refill kiosks, tap waters and bottled waters [J]. *Science of the Total Environment*, 2023,884:163866.
- [62] Galafassi S, Di Cesare A, Di Nardo L, et al. Microplastic retention in small and medium municipal wastewater treatment plants and the role of the disinfection [J]. *Environmental Science and Pollution Research*,

- 2022,29(7):10535-10546.
- [63] Zhang X, Feng X, Ma Y, et al. Comparison of chlorination resistance of biodegradable microplastics and conventional microplastics during the disinfection process in water treatments [J]. *Science of the Total Environment*, 2024,908:168229.
- [64] Liu Y, Wu X, Liu R, et al. Modifications of ultraviolet irradiation and chlorination on microplastics: Effect of sterilization pattern [J]. *Science of the Total Environment*, 2022,812:152541.
- [65] Zhang X, Lin T, Wang X. Investigation of microplastics release behavior from ozone-exposed plastic pipe materials [J]. *Environmental Pollution*, 2022,296:118758.
- [66] Li Y, Li J, Ding J, et al. Degradation of nano-sized polystyrene plastics by ozonation or chlorination in drinking water disinfection processes [J]. *Chemical Engineering Journal*, 2022,427:131690.
- [67] 米家辉,卢俊平,刘廷玺,等. 城镇污水厂各工序段对微塑料去除率差异特性分析 [J]. *中国环境科学*, 2024,44(6):3122-3131.
- Mi J H, Lu J P, Liu T X, et al. Analysis on the difference of microplastics removal efficiency in different working steps of urban sewage treatment plant [J]. *China Environmental Science*, 2024, 44(6):3122-3131.
- [68] Liu W, Zhang J, Liu H, et al. A review of the removal of microplastics in global wastewater treatment plants: Characteristics and mechanisms [J]. *Environment International*, 2021,146:106277.
- [69] Lin J, Wu X, Liu Y, et al. Sinking behavior of polystyrene microplastics after disinfection [J]. *Chemical Engineering Journal*, 2022,427:130908.
- [70] Shen M, Zhao Y, Liu S, et al. Can microplastics and disinfectant resistance genes pose conceivable threats to water disinfection process? [J]. *Science of the Total Environment*, 2023,905:167192.
- [71] Yuan Q, Sun R, Yu P, et al. UV-aging of microplastics increases proximal ARG donor-recipient adsorption and leaching of chemicals that synergistically enhance antibiotic resistance propagation [J]. *Journal of Hazardous Materials*, 2022,427:127895.
- [72] Shen M, Zeng Z, Li L, et al. Microplastics act as an important protective umbrella for bacteria during water/wastewater disinfection [J]. *Journal of Cleaner Production*, 2021,315:128188.
- [73] Nguyen H T, Lee Y K, Kwon J H, et al. Microplastic biofilms in water treatment systems: Fate and risks of pathogenic bacteria, antibiotic-resistant bacteria, and antibiotic resistance genes [J]. *Science of the Total Environment*, 2023,892:164523.
- [74] Nano/microplastics in water and wastewater treatment processes – Origin, impact and potential solutions [J]. *Water Research*, 2019,161: 621-638.
- [75] Tang A, Bi X, Du J, et al. The effect of polyethylene microplastics on the disinfection of *Escherichia coli* by sodium hypochlorite [J]. *Science of the Total Environment*, 2022,834:155322.
- [76] Ding W, Jin W, Cao S, et al. Ozone disinfection of chlorine-resistant bacteria in drinking water [J]. *Water Research*, 2019,160:339-349.
- [77] Adeel M, Maniakova G, Rizzo L. Tertiary/quaternary treatment of urban wastewater by UV/H₂O₂ or ozonation: Microplastics may affect removal of *E. coli* and contaminants of emerging concern [J]. *Science of the Total Environment*, 2024,907:167940.
- [78] Amelia D, Fathul Karamah E, Mahardika M, et al. Effect of advanced oxidation process for chemical structure changes of polyethylene microplastics [J]. *Materials Today: Proceedings*, 2022,52:2501-2504.
- [79] Ammar Y, Swailes D, Bridgens B, et al. Influence of surface roughness on the initial formation of biofilm [J]. *Surface and Coatings Technology*, 2015,284:410-416.
- [80] Manoli K, Naziri A, Ttofi I, et al. Investigation of the effect of microplastics on the UV inactivation of antibiotic-resistant bacteria in water [J]. *Water Research*, 2022,222:118906.
- [81] Adeel M, Granata V, Carapella G, et al. Effect of microplastics on urban wastewater disinfection and impact on effluent reuse: Sunlight/H₂O₂ vs solar photo-Fenton at neutral pH [J]. *Journal of Hazardous Materials*, 2024,465:133102.
- [82] Zheng J, Su C, Zhou J, et al. Effects and mechanisms of ultraviolet, chlorination, and ozone disinfection on antibiotic resistance genes in secondary effluents of municipal wastewater treatment plants [J]. *Chemical Engineering Journal*, 2017,317:309-316.
- [83] Galafassi S, Sabatino R, Sathicq M B, et al. Contribution of microplastic particles to the spread of resistances and pathogenic bacteria in treated wastewaters [J]. *Water Research*, 2021,201:117368.
- [84] Yang Z, Liu P, Wei H, et al. Alteration in microbial community and antibiotic resistance genes mediated by microplastics during wastewater ultraviolet disinfection [J]. *Science of the Total Environment*, 2022,825:153918.
- [85] 吴效俭,施国静,王莹莹. 微塑料影响抗性基因的传播与水平基因转移 [J]. *中国环境科学*, 2022,42(8):3957-3968.
- Wu X J, Shi G J, Wang Y Y. Effects of microplastics on the spread and horizontal gene transfer of antibiotic resistance genes [J]. *China Environmental Science*, 2022,42(8):3957-3968.
- [86] Guo Q, Wang M, Jin S, et al. Photoaged microplastics enhanced the antibiotic resistance dissemination in WWTPs by altering the adsorption behavior of antibiotic resistance plasmids [J]. *Science of the Total Environment*, 2024,919:170824.
- [87] Huang Y, Yu M, Wang Z, et al. Polyethylene microplastics decreased the chlorine disinfection efficacy of antibiotic resistant bacteria and antibiotic resistance genes [J]. *Journal of Water Process Engineering*, 2024,61:105233.
- [88] Xu Y, Huang D, Liu P, et al. The characteristics of dissolved organic matter release from UV-aged microplastics and its cytotoxicity on human colonic adenocarcinoma cells [J]. *Science of the Total Environment*, 2022,826:154177.
- [89] Lee Y K, Hong S, Hur J. Copper-binding properties of microplastic-derived dissolved organic matter revealed by fluorescence spectroscopy and two-dimensional correlation spectroscopy [J]. *Water Research*, 2021,190:116775.
- [90] Lee Y K, Romera-Castillo C, Hong S, et al. Characteristics of microplastic polymer-derived dissolved organic matter and its potential as a disinfection byproduct precursor [J]. *Water Research*, 2020,175:115678.
- [91] Lin T, Su J. The fate of microplastics and organic matter leaching behavior during chlorination [J]. *Chemosphere*, 2022,302:134892.
- [92] 刘建超,胡雍容. 聚氯乙烯和橡胶中化学成分的浸出行为及生态毒性 [J]. *中国环境科学*, 2022,42(11):5408-5417.
- Liu J C, Hu Y R. Leaching behavior and ecotoxicity of chemical

- composition in polyvinyl chloride and rubber [J]. *China Environmental Science*, 2022,42(11):5408-5417.
- [93] 苗令占,邓肖雅,杨 铮,等.微塑料的老化过程、产物及其环境效应研究进展 [J]. *中国环境科学*, 2023,43(11):6156-6171.
- Miao L Z, Deng X Y, Yang Z, et al. Research progress on the aging process, leachates of microplastics and their environmental effects [J]. *China Environmental Science*, 2023,43(11):6156-6171.
- [94] Ouyang Z, Zhang Z, Jing Y, et al. The photo-aging of polyvinyl chloride microplastics under different UV irradiations [J]. *Gondwana Research*, 2022,108:72-80.
- [95] Du Z, Li G, Ding S, et al. Effects of UV-based oxidation processes on the degradation of microplastic: Fragmentation, organic matter release, toxicity and disinfection byproduct formation [J]. *Water Research*, 2023,237:119983.
- [96] 郭 萌.氯化消毒过程中微塑料浸出溶解性有机物的行为及衍生消毒副产物的生成风险研究 [D]. 重庆:重庆大学, 2022.
- Guo M. Study on the behavior of microplastics leaching dissolved organic matter during the chlorination disinfection and the generation risk of disinfection by-products [D]. Chongqing: Chongqing University, 2022
- [97] Lee Y K, Yoo H Y, Ko K S, et al. Tracing microplastic (MP)-derived dissolved organic matter in the infiltration of MP-contaminated sand system and its disinfection byproducts formation [J]. *Water Research*, 2022,221:118806.
- [98] Chen B, Westerhoff P. Predicting disinfection by-product formation potential in water [J]. *Water Research*, 2010,44(13):3755-3762.
- [99] Romero-Esquivel L G, Grischek T, Pizzolatti B S, et al. Bank filtration in a coastal lake in South Brazil: water quality, natural organic matter (NOM) and redox conditions study [J]. *Clean Technologies and Environmental Policy*, 2017,19(8):2007-2020.
- [100] Hua L C, Lin J L, Chen P C, et al. Chemical structures of extra- and intra-cellular algogenic organic matters as precursors to the formation of carbonaceous disinfection byproducts [J]. *Chemical Engineering Journal*, 2017,328:1022-1030.
- [101] Goslan E H, Seigle C, Purcell D, et al. Carbonaceous and nitrogenous disinfection by-product formation from algal organic matter [J]. *Chemosphere*, 2017,170:1-9.
- [102] 张 显,英 浩,刘 航,等.臭氧预氧化对微塑料消毒副产物生成势的影响 [J]. *环境科学学报*, 2023,43(10):108-115.
- Zhang X, Ying H, Liu H, et al. Effect of pre-ozonation on disinfection byproduct formation from microplastics upon subsequent chlorination [J]. *Journal of Environmental Sciences*, 2023,43(10):108-115.

作者简介: 赵思凯(1999-),男,四川乐山人,重庆交通大学硕士研究生,主要研究方向为水污染控制技术及原理.发表论文 1 篇.