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我国三大水系环境微塑料污染现状及其表面微生物群落特征的研究进展

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摘　要：微塑料(microplastics, MPs)广泛存在于水生生态系统表层，可为水环境中微生物的富集提供独特的生态位，并对生态系统及人类健康造成潜在威胁。我国是塑料生产及使用大国，正面临着严重的塑料污染问题，我国水系的微塑料污染状况及其表面微生物群落的生态效应受到重点关注。本文总结了我国三大水系(长江、黄河、珠江)微塑料污染现状、微塑料表面微生物群落的分布特征及影响因素，最后对我国水环境中微塑料表面的微生物研究现状和未来发展提出总结与展望。

关键词：微塑料；污染特征；微生物群落；影响因素

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Research progress in microplastic pollution status and microorganisms on microplastics in three major rivers in China

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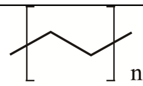
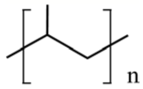
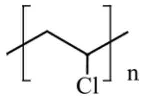
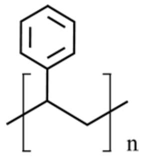
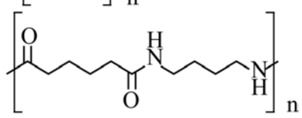
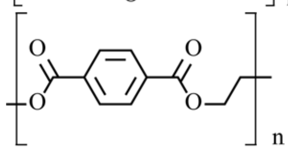
Abstract: Microplastics (MPs) are ubiquitous in the surface water of aquatic ecosystems. Generally, MPs can provide unique niches for microorganisms in the environment and pose potential threats to ecosystems and human health. China produces and uses a large amount of plastics, which results in serious plastic pollution. The pollution of MPs in aquatic ecosystems in China and the ecological effects of the microbial communities on MPs have aroused increasing concern. This review introduced the status of MP contamination in three major rivers (Pearl River, Yangtze River, and Yellow River) in China, the microorganisms on MPs, and the factors influencing the microbial community structure. Finally, we summarized the research progress in the microorganisms on MPs in China's aquatic ecosystems and put forward the prospects.
Keywords: microplastics; contamination characteristics; microbial community; influencing factors

塑料因生产成本低、防水性强等优点被广泛应用于各个领域[1-2]。全球范围内塑料的年产量已超过 3 亿 t，但其难以被自然降解，在不同水生生境中的废塑料制品可被动物误食，导致动物窒息而死。此外，塑料可在土壤内积累，影响农作物吸收水分，导致农作物减产并污染地下水，造成严重的环境污染问题[3]。塑料制品可在物理、化学和生物等外界环境因素的作用下被分解为塑料颗粒[4]。微塑料(microplastics, MPs)是指直径小于 5 mm 的塑料颗粒[5]，占塑料垃圾的92.4%[6]，其主要聚合物类型有聚乙烯(polyethylene, PE)、聚丙烯(polypropylene, PP)、聚苯乙烯(polystyrene, PS)及聚对苯二甲酸乙二醇酯(polyethylene terephthalate, PET)等[7] (表 1)。与塑料污染相比，微塑料污染可导致更严重的环境、生态和健康问题。微塑料具有分布广、粒径小和比表面积大等特点[10]，其进入水环境时易吸附农药及重金属等污染物[2]，产生复合毒性效应[11-12]，对人体健康造成潜在威胁[4]。这些特点也使得微塑料成为环境中微生物定殖及扩散的独特载体[13-14]。已有研究探究了水体中塑料表面的微生物群落组成及结构，其与周围水体及自然基质中的群落相比有显著差异[15]，其中的微生物以细菌群落为主[16-17]。

长江、黄河及珠江是我国三大水系，所在区域人口密集、经济发展迅速，其生态环境的健康对我国人类居住的安定及社会经济的可持续发展而言至关重要。已有许多研究关注了长江、黄河及珠江流域的微塑料污染情况，与世界上其他水生环境相比，它们受到的微塑料污染程度更

表 1 淡水环境中常见的微塑料聚合物类型及其用途[8-9]

Table 1 Polymers types and applications of MPs commonly found in freshwater[8-9]

Polymer	Structure	Application
聚乙烯 Polyethylene (PE)		Film, plastic bag, plastic bottle, disposable cup, etc.
聚丙烯 Polypropylene (PP)		Carpet, bathtub, fishing net, textiles, etc.
聚氯乙烯 Polyvinyl chloride (PVC)		Construction industry (pipeline, fence, floor, etc.)
聚苯乙烯 Polystyrene (PS)		Disposable meal box, insulation board, etc.
聚酰胺 Polyamide (PA)		Fishing gear, plastic glove, meter case, toothbrush, etc.
聚对苯二甲酸乙二醇酯 Polyethylene terephthalate (PET)		Fiber, film, audiotape, food packaging, etc.

深，影响更大。据 Lebreton 等[18]的模型估计，长江及珠江分别是世界上微塑料污染第一及第三严重的区域。而 Ding 等[19]的研究表明，黄河部分流域的低流量和高含沙率有利于微塑料颗粒的沉积，导致此地沉积物中微塑料的高丰度。基于此，本文总结了我国三大水系中微塑料的污染情况及其表面微生物群落的分布特征，旨在为微塑料污染的原位修复及微塑料表面微生物的研究提供一定的科学信息参考。

1 三大水系微塑料的污染特征

以下总结了珠江、长江及黄河水系中微塑料的分布及污染特征，包括干流水域、支流水域、河口地区及红树林地区(表 2)。

1.1 微塑料的主要聚合物类型及主要来源

微塑料的主要聚合物类型随着地区的不同而不同，总体而言，聚乙烯(PE)及聚丙烯(PP)是三大水系中微塑料的主要聚合物类型，这可能是由于 PE 及 PP 是全球塑料产量最大的两类，它们常被用于包装、纺织品和渔具等[34-35]。此外，研究表明在水环境中由不同材料组成的微塑料具有不同的环境行为，高密度聚合物(如 PET 及 PVC)在沉积物中的丰度较表层水的大，这可能是由于高密度的微塑料更容易沉降到底泥中并吸附在沉积物表面[25,29]。

对三大水系的微塑料形状总结发现，纤维(fiber)是最主要的形状类型。实验研究发现，每次机洗可脱落 1 900 多根纤维，平均 6 kg 丙烯酸纤维织物洗涤负荷可释放 70 多万根纤维[36]。洗衣机废水中的这些纤维将被输送到污水处理厂。这些纤维中的一部分能够穿过污水处理厂的滤网，进入水生环境[36-37]。此外，渔业及纺织业等行业也会产生大量的微塑料纤维[38]，这些人类活动可能是导致该研究结果的主要原因。碎片(fragment)、薄膜(film)和颗粒(pellet)在三大水系中的含量也相对较大，相关调查显示，碎片可能

表 2　三大水系微塑料污染现状总结

Table 2　Summary of MPs pollution in Pearl River, Yangtze River and Yellow River

Region	Site	Sample	Main polymer	Main size	Main color	Shape	Average abundance	Reference
Pearl River								
珠江三角洲八大河口 8 major outlets in the Pearl River Delta	虎门 Humen	Surface water	PP (43.1%) PE (39.0%)			Fiber (53.1%) Fragment (13.1%) Film (13.1%) Foam (11.4%) Pellet (1.27%)	0.139 items/m³	[20]
	蕉门 Jiaomen						0.024 items/m³	
	洪奇门 Hongqimen						0.008 items/m³	
	横门 Hengmen						0.547 items/m³	
	磨刀门 Modaomen						0.065 items/m³	
	鸡啼门 Jitimen						0.014 items/m³	
	虎跳门 Hutiaomen						0.014 items/m³	
	崖门 Yamen						0.041 items/m³	
珠江流域 Pearl River Basin	流溪河 Liuxihe Dam	Surface water	PP (61.8%) Rayon (23.5%)	<2 mm (94.83%)	White (29.81%) Black (21.18%)	Fragment (56.29%) Film (31.14%)	0.85 items/m³	[21]
	穗石港口 Suishi Harbor entrance		PP (63.3%) PE (32.7%)			Fragment (60.96%) Film (22.75%)	1.95 items/m³	
	东江下游 Dong River downstream		PP (50%) PE (42.2%)			Fragment (48.06%) Fiber (18.93%)	1.30 items/m³	
	西江 Xi River		Rayon (76.9%)			Fiber (100%)	0.14 items/m³	
	石马河 Shima River		PP (61.1%) PE (33.3%)			Fragment (71.43%) Film (14.29%)	0.78 items/m³	
	北江 Bei River		Rayon (64.7%)			Fiber (94.62%)	0.91 items/m³	
珠江广州城市段和河口 Pearl River along Guangzhou City and Pearl River estuary	城市段 Urban Section	Surface water	PA (26.2%) Cellophane (23.1%)	<0.5 mm (80%)	Blue (38%) Transparent (37%)	Film (52%) Pellet (41%)	19 860 (8 725–53 250) items/m³	[22]
	河口 Estuary					Pellet (48%) Film (43%)	8 902 (7 850–10 950) items/m³	
广州河段 Guangzhou section of Pearl River		Surface Water	PE (34.62%) PP (29.84%)	<0.5 mm (36.16%)	White (52.10%) Colorful (20.27%)	Pellet (67.90%) Film (12.50%)	1.74 items/L	[9]
		Sediment (dw)	PE (36.04%) PP (23.42%)	<0.5 mm (42.57%)	White (52.71%) Colorful (30.05%)	Pellet (67.98%) Sphere (15.76%)	556.7 items/kg	

(待续)

(续表 2)

Region	Site	Sample	Main polymer	Main size	Main color	Shape	Average abundance	Reference
珠江口香港海岸线25个泳滩 25 beaches along the Hong Kong coastline at Pearl River Estuary	后海湾水质管制区 Deep Bay	Sediment (dw)	EPS (92%)	0.315–5 mm (over 90%)			106 items/m^3	[23]
	大鹏湾 Mirs Bay						1 834 items/m^3	
	西北部 North Western						2 349 items/m^3	
	牛尾海 Port Shelter						400 items/m^3	
	南区 Southern						15 554 items/m^3	
	吐露港 Tolo Harbour						382 items/m^3	
	维多利亚港 Victoria Harbour						5 399 items/m^3	
珠江口3个滨海红树林3 Mangrove wetlands of The Pearl River estuary	深圳福田红树林自然保护区 Futian Mangrove Nature Reserve	Sediment (dw)	PP-PE (77.5%)	<0.5 mm (77.3%)	Black (28.3%) Green (43.1%)	Fiber (69.7%) Fragment (27.8–28.9%)	1 449 items/kg	[24]
	南沙滩头红树林自然保护区 Tantou Mangrove Nature Reserve		PP-PE (68.8%)	<0.5 mm (52.3%)	Black (35.2%) Green (27.0%)		597 items/kg	
	珠海淇澳岛红树林自然保护区 Qi'ao Island Mangrove Nature Reserve		PP-PE (56.4%)	<0.5 mm 50.6%	Black (47.6%) Green (21.1%)		316 items/kg	
珠江干流及部分支流 The main stream and the tributaries of Pearl River	干流 Main stream	Sediment (dw) /Water	PP, PE and PP-PE		White and transparent	Sheet fiber fragment	928 items/kg/ Spring 0.37 & Summer 0.35 & Winter 1.96 items/L	[25]
	北江 Beijiang River						132 items/kg/ Spring 0.14 & Summer 0.14 & Winter 0.36 items/L	
	东江 Dongjiang River						604 items/kg/ Spring 0.25 & Summer 0.24 & Winter 0.64 items/L	
	西江 Xijiang River						586 items/kg/ Spring 0.22 & Summer 0.27 & Winter 0.43 items/L	

(待续)

(续表 2)

Region	Site	Sample	Main polymer	Main size	Main color	Shape	Average abundance	Reference
Yangtze River								
长江中下游水系 Middle and lower Yangtze River	太湖 Taihu Lake	Water	Polyesters, semipolymers and PP	<1 mm (68.0%)	Blue	Fiber (76%)	3.4–25.8 items/L	[26]
		Sediment (dw)		<1 mm (80%)	Transparent, white and black (over 70%)	Fragment (34%)	11.0–234.6 items/kg	
	长江口滩涂至鄱阳湖 Yangtze estuary to Poyang Lake	Water		<1 mm	Blue and transparent (over 50%)	Fiber (over 70%)	0.7–2.2 items/L	
		Sediment (dw)		<1 mm (over 80%)	Transparent, white and black (over 60%)	Fiber (over 80%)	22.8–83.8 items/kg	
长江口 Yangtze River estuary		Surface water	PE and PP	<1 mm (75%)		Fiber (77.8–91.6%)	157.2 items/m^3	[27]
		Sediment (dw)	Rayon (63.1%) Polyester (18.5%)	<1 mm (58%)	Transparent (42%)	Fiber (93%)	20–340 items/kg	[28]
长江中下游 18 个重要湖泊 18 lakes along the middle and lower reaches of the Yangtze River	淀山湖、太湖、滆湖、花神湖、固城湖、巢湖、白荡湖、菜子湖、龙感湖、鄱阳湖、策湖、东湖、南太子湖、梁子湖、斧头湖、洪湖、洞庭湖和大通湖 Dianshan, Taihu, Ge, Huashen, Gucheng, Chao, Baidang , Caizi, Longgan, Poyang, Ce, Dong, Nantaizi, Liangzi, Futou, Hong, Dongting and Datong	Surface water	PP (67.21%)	<1 mm (52.16%)	Blue (41.10%)	Fiber (93.81%)	780 items/m^3	[29]
		Sediment (dw)	PP (62.68%)	<1 mm (65.95%)	Blue (69.11%)	Fiber (94.77%)	219 items/kg	
Yellow River								
黄河下游近河口流域 The lower Yellow River near estuary		Surface water	PE, PP and PS	<0.2 mm (87.94%)		Fiber (93.12%)	Dry season: 930 items/L Wet season: 497 items/L	[30]
黄河上游、中游及下游流域 The upper, middle and lower reaches of the Yellow River	Upper reaches	Surface water	PE (63.7%)	<2 mm	Colorful	Fiber (68.18%–78.64%)		[31]
	Middle reaches			<0.5 mm (68.1 %)		Fiber (50.1 %)	3.67–10.7 items/L	[19]
	Lower reaches		PE, PP and PS	50–200 μm		Fiber	595.27 items/L	[32]
	Estuary			50–200 μm		Fiber	Dry season: 930.2 items/L Wet season: 654 items/L	
	Upper reaches	Sediment (dw)	PE, PP and PS	1–4 mm (64.8%)	Transparent (43.28%) White (34.55%)	Fragment (43.35%) Foam (34.08%)	43.57 items/kg	[33]
	Middle reaches						54.29 items/kg	
	Lower reaches						273.75 items/kg	
	Estuary						615 items/kg	

EPS: Expanded polystyrene; dw: Drained weight; PP-PE: Polypropylene-polyethylene copolymer.

来自于日常生活中塑料材料的破碎，如塑料容器、包装材料等[31]。薄膜状微塑料可能来源于塑料袋、农业地膜等的大量使用[9,31]。而微珠则可能主要来源于化妆品，如面部清洁剂、沐浴液和牙膏[39]。综合微塑料聚合物类型及形状的信息可以帮助进一步估计微塑料的主要来源,并有针对性地采取有效措施控制其排放量。

1.2 微塑料的主要粒径及颜色加深其生态危害效应

研究表明三大水系中的微塑料粒径均较小,这可能是因为在环境中更大粒径的微塑料及较大的塑料碎片可在风化、磨损等外力因素的作用下裂解成大量的小粒径微塑料，此外，小粒径微塑料可能更容易通过污水处理厂的滤网,并随着处理后的污水流入河流中[9,40]。微塑料的颜色种类丰富，这可能是受到塑料消费市场影响。商家为了吸引消费者，会倾向于生产彩色的塑料制品[9]，从而导致环境中微塑料颜色的多样化。较小的微塑料可能具有较大的比表面积,这将增加其吸附其他污染物的能力,如持久性有机污染物(persistent organic pollutants, POPs)和内分泌干扰物(endocrine disrupting chemicals, EDCs)，从而威胁生态系统的健康[41-42]。此外，较小的微塑料更倾向于被生物吞食或缠绕[43]。有色微塑料也更容易被生物捕获，从而更容易进入食物链[44]。微塑料的小粒径及多样的颜色加深了微塑料的生态危害效应,这需要人们进一步地关注与重视。

1.3 微塑料丰度的空间变化

本文对我国三大水系的微塑料污染情况总结发现，微塑料的空间分布呈现出相似的模式，人类活动密集的区域通常具有更高的微塑料丰度,而具有较低的人口密度的区域通常具有较低的微塑料污染程度。Vianello 等[45]的研究发现，与人类输入相关的微污染物与微塑料分布具有高度相关性,这表明微塑料的主要来源是人类活动[28]。Yan 等[22]研究了珠江在河口区域及广州市内的微塑料污染情况,结果显示广州城市段的珠江水域的微塑料丰度明显高于珠江口样品。这表明城市污水可能是珠江中微塑料的主要来源，而城市支流可能是微塑料的滞留系统。在 Peng 等[28]的研究中,上海东南沿海靠近黄浦江和白龙港污水处理厂的微塑料浓度最高,而最低的微塑料浓度出现在长江口外部。牛学锐[32]对黄河下游及入海口表层水的微塑料丰度进行了调查,结果显示表层水体中的微塑料丰度与距离河口的远近有显著的线性相关关系。这些研究进一步证明了人类活动对微塑料污染程度的显著影响。此外，这些结果也暗示了河流运输是陆源塑料碎片向海洋环境传递的主要途径[46-47],说明了对河流水系进行微塑料污染情况研究的重要性。水系中微塑料的丰度及分布还可能会受到河流水文特征的影响,在河流系统中,微塑料运输取决于水流，流量较大的河流具有较高的运输大量颗粒的能力[48]。在河流缓慢流动的中下游区域，微塑料更有可能与下沉的沉积物颗粒一起沉降并被掩埋。龚喜龙等[33]比较了黄河上、中、下游沉积物中的微塑料丰度,结果显示下游的微塑料丰度明显高于上游和中游,且微塑料的丰度呈现出由上游至下游逐渐增加的趋势,这可能受到黄河流速从上游到下游渐缓的影响,更多的微塑料在下游随着泥沙沉积到底部。

1.4 微塑料丰度的季节变化

本文总结发现,季节的变化以及降雨量的多少,直接或间接影响了我国三大水系表层水及沉积物的微塑料丰度。程瑶[20]调查了珠江三角洲八大主要河口表层水体的微塑料污染情况。雨季(4 月、6 月及 8 月)的微塑料丰度显著高于旱季(1 月及 11 月)，表现出水体中微塑料的浓度随降雨频率及降雨强度的增大而升高的特点。类

似地，据 Cheung 等[49]调查显示，香港西部区域的珠江河口在旱季微塑料总丰度的平均值为 889 items/m^2，显著低于雨季的 5 595 items/m^2。Zhao 等[27]的研究表明，相比 2 月及 5 月，在降雨量更高的 7 月份，采集的长江口样品的微塑料丰度更高。这可能是雨季降雨量大使得河流流量变大，更多的塑料垃圾通过地表径流运输到河口区域所致。与之不同的是，Fan 等[25]调查了珠江干流及其部分支流的微塑料污染情况，结果发现雨季(春季至夏季)的微塑料丰度较旱季(秋季)低，这可能归因于降水的稀释效应。这些调查结果表明，在进行微塑料污染情况调查时需考虑到季节变化对微塑料丰度的影响，如果只在雨季或旱季进行研究，对微塑料污染状况的估计可能会有较大的偏差。

具体而言，长江、黄河及珠江水系的微塑料污染情况各不相同。相比黄河地区，长江及珠江沿岸经济发展迅速，人口密度大，因而有着更高的微塑料污染水平。此外，长江及珠江地区有着悠久的渔业历史，渔线、渔网等渔业制品的磨损及风化被认为是水系中纤维状微塑料的主要来源；黄河地区农业实践较多，农用肥料编织袋、农用地膜的丢弃被认为是水系中微塑料污染的重要来源之一。

2 三大水系微塑料表面附着微生物的群落结构特征

2.1 微塑料表面微生物定殖的原理

在水生环境中，微生物在聚合物表面的黏附及定殖的关键是在微塑料表面形成生物被膜。微塑料具有比表面积大、吸附能力强及难降解的特点，表面可吸附各种有机物，因而可为微生物提供稳定的栖居环境及丰富的营养底物[50-51]。在水系环境中，细菌可在微塑料表面迅速寄居并大量生长繁殖，形成生物被膜(biofilm)，并在其中形成一个由异养菌、自养菌及共生体等组成的多样化的微生物群落[52]。微塑料生物被膜的形成一般可分为 4 个过程：细菌附着、菌体分泌胞外多聚物(extracellular polymeric substances, EPS)、细菌增殖和形成生物膜(图 1)。

2.2 三大水系中微塑料表面的微生物物种组成

已有许多研究采用扩增子测序或宏基因组学的方法，探究了水系环境中微塑料表面的微生物群落组成，主要以变形菌门(*Proteobacteria*)、拟杆菌门(*Bacteroidetes*)及厚壁菌门(*Firmicutes*)为主。如 Yang 等[54]曾探究了珠江三角洲河流中微塑料生物膜的微生物组成，结果表明，变形菌门的相对丰度最高，厚壁菌门是第二大优势菌门。Jiang 等[55]分析了长江口潮间带微塑料样品的细菌群落组成，主要包括变形菌门、蓝细菌门、拟杆菌门及放线菌门等。这些结果与此前关于海洋的研究类似[56-58]。这可能是由于这些菌群在生物膜形成过程中发挥着重要的作用，许多研究表明，在塑料表面形成生物膜的微生物具有物种特异性，变形菌及拟杆菌是水环境中基质表面的主要及次要殖民者[59-62]。

2.3 微塑料表面富含潜在病原菌

许多研究显示，在环境中微塑料可作为一个独特的生态位，并可在其表面富集更多的潜在致病菌[51,63-64]。这些滞留在微塑料上的潜在病原体可以进入食物链，并转移到不同的营养级水平。这可能会对生态系统、商业养殖和人类健康产生不利影响[65-67]。Yang 等[54]在采集来的处于珠江八大河口流域的样品中，均检出含有致病类群的假单胞菌属(*Pseudomonas*)、不动杆菌属(*Acinetobacter*)、沙雷氏菌属(*Serratia*)和梭菌属(*Clostridium*)。它们中的部分物种，如铜绿假单胞菌(*Pseudomonas aeruginosa*)[68]、鲍曼不动

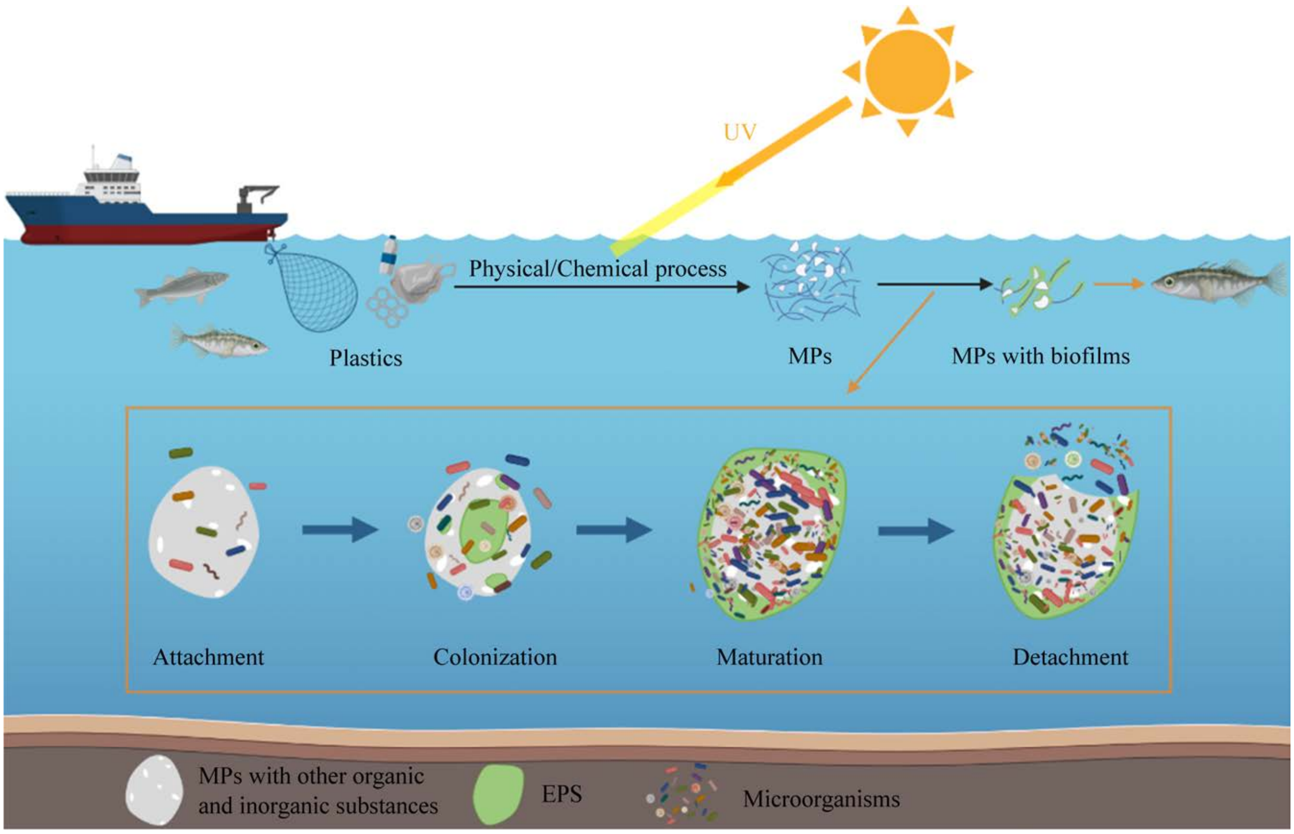


图 1　河流水系中微塑料表面生物被膜的形成过程[52-53]

Figure 1　Succession of biofilm on the surface of MPs in the rivers[52-53].

杆菌(*Acinetobacter baumannii*)[69]、粘质沙雷氏菌(*Serratia marcescens*)[70]及肉毒杆菌(*Clostridium botulinum*)[71]等是典型致病菌，可引起炎症感染、头晕、呼吸困难等症状，甚至可导致死亡。在 Jiang 等[55]的研究中，弧菌属(*Vibro*)及含有脓毒假单胞菌(*Pseudomonas anguilliseptica*)的假单胞菌属也在部分样品中被检出。这些细菌类群被认为对鱼、虾和贝类等水生动物具有致病作用，并可以通过食物链的传递对人类健康造成不良影响[64,72]。

2.4　微塑料表面微生物携带并传播抗生素抗性基因

近年来，携带抗生素抗性基因(antibiotics resistance genes, ARGs)的耐药细菌受到热点关注。部分研究显示，水环境中的微塑料表面微生物对 ARGs 具有富集作用[13,73-74]。Guo 等[61]探究了黄浦江内微塑料表面生物膜中 ARGs 的丰度，结果表明，生物膜中总 ARGs 的平均绝对丰度达 1.97×10^8 copies/g，显著高于环境沉积物中的 ARGs 丰度(4.60×10^7 copies/g)。这些生物膜中的 ARGs 很可能以微塑料为载体从而在各种水环境中广泛传播，并在细菌间发生频繁的水平基因转移事件，显著影响水生微生物群落的生态，并最终对人类健康造成不可忽视的危害[75-76]。

2.5　微塑料表面存在塑料降解菌

有研究表明，生物被膜中的部分微生物能够分解微塑料，并将代谢物作为碳或能量来源[77]。Yan 等[78]调查了珠江口 4 个红树林内沉积物的微塑料污染及微塑料表面微生物群落情况，结果表明，与红树林沉积物中的细菌群落相比，微塑料表面的细菌群落似乎具有更高的降解苯甲酸酯

和己内酰胺的能力，它们都是塑料生产中所需的材料[79-80]。Niu 等[81]探究了秦淮河沉积物中微塑料表面塑料降解菌的存在情况。与环境沉积物中的细菌群落相比，微塑料表面具有更多的塑料降解菌，且分泌更多的塑料水解酶，这或许能为塑料降解菌资源的挖掘提供一定的信息参考。

3 微塑料表面微生物群落结构的影响因素

在水系环境中，微塑料表面微生物群落分布除了在宏观上受到水文、季节及营养的影响外，还受到自身附着微环境的影响，如微塑料自身的结构属性等。

3.1 微塑料的理化性质

以往研究表明，微生物的定殖受到微塑料聚合物性质的影响，包括疏水性、粗糙度、结晶度和晶体结构等[82-83]。作者团队曾探究了珠江河口生境中不同微塑料(PLA、PP 及 PS)表面原核微生物的多样性和群落组成的动态变化，β 多样性分析结果显示，随时间延长，不同颗粒物表面原核微生物群落组成差异逐渐增大，颗粒物种类可能对其表面定殖的原核微生物类群具有较强的选择作用。Guo 等[61]曾在黄浦江生境中探究了 3 种塑料样品(PE、PP 及 PET)上生物膜的形成情况，发现 PE 和 PET 形成的生物膜比 PP 具有更大的生物量。在 PP 表面，变形菌门的丰度达 81.9%，显著高于 PE (53.06%)及 PET (37.06%)，而在 PE 及 PET 上蓝细菌门的丰度显著高于 PP。该结果可能与 PE 及 PET 表面润湿性较低有关。

3.2 环境条件

多数学者认为，微塑料表面的微生物群落组成主要受到实际环境条件的影响[84-86]。Yang 等[54]采用了冗余分析(redundancy analysis, RDA)的方法探究了 15 个环境变量对微塑料表面微生物群落组成的影响。结果表明，无机碳含量(inorganic carbon content, IC)、碱度、有机碳总量(total organic carbon, TOC)、可溶解固体总量(total amount of dissolved solids, TDS)、Cl^-、NO_3^-、NO_2^-及 pH 值与微塑料表面生物膜群落结构显著相关。

4 总结与展望

微塑料作为一种新型污染物，其污染水平、赋存状态及对水生生态系统的危害已引起广泛关注。本文对我国主要水系(长江、黄河及珠江)的微塑料污染水平、赋存状况及时空分布等进行了总结。河流水系是微塑料向海洋传递的主要运输途径，微塑料在水系中的丰度及分布受到水文特征及人类活动的影响，并呈现出季节性的变化。环境中微塑料形态各异、颜色多样，且多为小粒径微塑料，这些特征使得微塑料更容易被生物摄入进入食物网，进而对人类健康造成潜在威胁。在水环境中，微塑料可为微生物提供独特的生态位，其表面富集致病菌及耐药菌，这可能会促进疾病的传播及“超级细菌”的出现，与之相关的研究有待进一步开展。另一方面，微塑料表面也被发现含有较多的塑料降解菌，它们具有更高的水解酶活性，这为塑料降解菌资源的挖掘提供了一定的思路与启示。为了更好地了解我国水系微塑料污染风险及特征，需要对以下方面进行研究与阐明：

(1) 内陆地表水微塑料污染情况的研究仍有待补充。目前有关我国水系环境中微塑料污染情况的研究主要集中在入海口及河口城市区域。而有关内陆地表水的研究十分欠缺，这一不足限制了对河流水系中微塑料整体分布规律的理解。这些信息的补充有助于更全面地探究水系中微塑料赋存及运输的特点，并更好地了解水系中微塑料的污染源头及重污染区域，从而有针对性地进行治理。

(2) 微塑料富集致病菌及耐药菌的机制有待进一步阐明。微塑料表面富集的重金属、多环芳烃等污染物如何影响微生物群落结构与生态功能,它们是否促进了致病菌的富集及耐药菌的出现。这些问题的探究有助于进一步揭示微塑料提供独特生态位的原因,并加深对微塑料复合污染效应的理解。

(3) 确定参与微塑料表面微生物基因交换的关键微生物种类。这将有助于更好地理解微塑料表面水平基因转移事件的发生过程,从而更好地评估微塑料表面 ARGs 富集及传递所带来的健康风险。

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