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水环境中微塑料的分布迁移特征及生态危害研究进展

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摘要: 微塑料是重要的环境污染物之一,在水环境中大量存在。为了解水环境中微塑料污染的现状,增强人们治理微塑料污染的意识,本文概述了水环境中微塑料的来源、分布、迁移特征及对水生动物的危害。水环境中的微塑料来源广泛,源头贡献分析发现,环境中80%的微塑料来源于人类陆地活动,20%来源于海洋活动。按性质分类,微塑料可分为初生微塑料、次生微塑料两大类,碎片、纤维是水环境中最常见的微塑料形态,淡水中主要的微塑料类型是聚乙烯(PE)、聚丙烯(PP),海洋中的微塑料类型则主要是PE、PP和聚苯乙烯(PS)。水环境中的微塑料含量、分布主要受到区域人口密度、地理位置、水文条件和气象环境等因素影响,微塑料在水系统表面和沉积物中均有分布,淡水系统是微塑料进入海洋的主要运输路径。微塑料通过直接、间接方式进入水生生物体内,导致其群体、个体、组织、器官、细胞和分子水平上的生理健康受损。水生态系统中的微塑料会给环境及动物健康带来不同程度的风险,进一步通过食物链威胁人类健康。微塑料污染研究的重点应包括制定厘清源头、查明分布、科学监测的综合治理模式。本文可为水环境中微塑料的污染防治提供较为系统的参考资料和研究思路。

关键词: 微塑料; 水环境; 来源; 迁移; 生态危害
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Research progress on distribution and migration characteristics and ecological hazards of microplastics in water environment

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Abstract: As a new environmental pollutant, microplastics are abundant in water ecosystems and bring great harm to aquatic life. In order to comprehensively understand the current situation of microplastic pollution and enhancing people's awareness of microplastic pollution control, this paper reviewed the source, distribution migration characteristic and ecological hazard in water environment. Microplastics have a wide range of sources. According to the perspective of microplastic properties, they are mainly derived from primary microplastics and secondary microplastics. Based on analysis of source contribution, the 80% of the microplastics come from human activities and 20% from marine activities. Fiber and debris are the main forms of microplastics in water environment. The main types of microplastics in freshwater are polyethylene (PE) and polypropylene (PP), but PE, PP and polystyrene (PS) in seawater. The contents and distributions of microplastics in water environment are mainly affected by population densities, geographical locations, hydrological conditions and meteorological environments. The microplastics are distributed on the surface of water system and sediment. The main transport route of microplastics is from

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freshwater system into seawater. Microplastics enter aquatic organisms directly or indirectly, resulting in physiological health damage on population, individual, tissue, organ, cell and molecular levels. In conclusion, microplastics in water ecosystems could bring different degrees of risk to the environment and the health of animals, and further threaten human health through the food chain. In the future, the study on microplastic pollution in water environment will focus on traceability, distribution identification and scientific monitoring. This review provides a systematic reference and research ideas for the pollution prevention of microplastics in water environment.

Key words: microplastic; water environment; source; migration; ecological damage

塑料制品用途广泛,目前全球的塑料制品产业规模持续增长[1-3]。据统计,当前全球每年的塑料产量约为3.48×10^8 t,预计到 2050 年,全球每年的塑料产量将达到3.3×10^{10} t[4]。塑料垃圾会在机械破碎、水侵蚀、紫外线降解、生物降解和光降解等作用下逐渐解离成破碎片状,变成微塑料[5-6]。

微塑料是指直径小于 5 mm 的塑料碎片[7-9]。随着环境安全检测技术的持续进步,人们相继在海洋[10]、大气[11]、湖泊[12]、河口[13]等处发现了微塑料。由于微塑料具有浮力和难降解性,其广泛分布在从北极到南极的全球海洋、海岸线、海滩、海底沉积物和地表水中,并通过水动力和洋流漂浮在偏远地区[14-15]。鉴于塑料制品的大量生产和使用,塑料废弃物会不可避免地进入水环境中。据估算,全球海洋表面漂浮的塑料垃圾已超过2.50×10^5 t[16],成为海洋和淡水生态系统中普遍存在的环境污染物,对水生生态系统构成了巨大威胁[17]。目前微塑料污染问题及其对水体环境的潜在风险已引起了研究人员的广泛关注。

虽然目前关于水环境中微塑料的研究较多,但仍缺乏对相应研究成果的系统整理,不利于研究人员从整体上把握微塑料研究的现状与趋势。因此,本文拟通过对全球水环境中微塑料污染的研究现状进行分析总结,分析水环境中微塑料污染的来源、时空分布特征以及水环境中微塑料污染的潜在生态危害,并为微塑料污染防治的研究思路提出相应建议,以期为相关研究人员提供参考。

1　水环境中微塑料的来源

水环境中的微塑料可分为初生微塑料、次生微塑料两大类。初生微塑料主要从陆地直接排放到自然水体中。塑料工业中使用的树脂颗粒以及用于生产卫生用品、个人护理品(化妆品、防晒霜、磨砂膏和清洁剂)、驱蚊剂、合成基钻井液和喷气介质的塑料前体都属于初生微塑料[18]。其中,生产个人护理品使用的塑料微珠直径约为 5 mm[19],通过废水和工业泄露排入自然水体中,并最终随着河流汇入海洋环境中[20]。

次生塑料是由较大的塑料物品破碎形成的。一方面,塑料在紫外线的光氧化作用下,会发生化学键的断裂,从而降低塑料的拉伸强度,引起塑料崩解[7]。另一方面,塑料制品在使用或风化过程中产生的机械应力、光化学作用和化学作用均可导致塑料脆化成小碎片[21]。在降解速度方面,在野外直接暴露于地表的塑料,由于直接接触光和氧气,使其降解速度较快,同时,阳光也可以使温度升高,从而进一步加快塑料的降解过程。而在海洋中,随着深度的增加,塑料的降解速度逐渐降低,在海底的降解速度几乎为零[7]。在水环境中,塑料与天然沉积物之间的相互作用(如河流的湍流冲击和海浪的驱动)产生的机械应力是形成次生塑料的重要原因[22]。此外,人造草皮和人工操场的磨损、汽车刹车和轮胎磨损、油漆和沥青等也会产生次生微塑料[23],这些微塑料会通过风、雨水和河流由陆地进入水系统,最终汇入海洋。大多数通过初生或次生过程形成的微塑料在环境中还会继续降解,甚至达到纳米级(<1 μm),或者在未知时间尺度上持续降解,直至聚合物完全降解成二氧化碳、水和生物质[24]。

相关统计结果表明,人类的陆地活动贡献了 80%的环境塑料来源,而海洋活动的贡献比例为 20%[25]。在不同地点发现的微塑料类型与周围人类活动之间存在较强的空间相关性[26]。因此,根据聚合物类型及其浓度亦可对微塑料进行溯源。例如,在北美五大湖地区发现的微塑料的大小、形状、颜色和元素组成与洗面奶中的微塑料相似,而污水处理厂中发现的塑料颗粒的颜色、形状和大小与牙膏配方中的塑料微粒具有较高的相似度[27]。以上研究结果表明,在淡水环境中,个人护理品中含有的塑料微粒可能是主要的

微塑料污染来源。Lechner 等[26]发现,多瑙河中的微塑料可能来源于该流域内德国的几十个塑料生产基地和数量不详的加工公司。Eriksen 等[28]则在美国休伦湖工业区附近的伊利湖中发现了工业树脂颗粒和微球。相反,在人类活动较少的偏远山区和湖泊中则几乎没有发现原生微塑料污染,但在那里也发现了大量次生塑料污染[29]。

2 水环境中微塑料的分布特征

2.1 微塑料在淡水环境中的分布特征

聚乙烯(PE)、聚丙烯(PP)是淡水中主要的微塑料类型,二者被人们广泛使用,且密度小于水,更易被检测。由于污染源、地理位置和水动力条件的差异,淡水中微塑料的类型与海洋中的不同[13]。在中国太湖水域和黄河水域,水体中的微塑料以纤维为主,比例在 60%以上[30-31];而在珠江水域,水体中主要的微塑料类型为碎片[32]。在蒙古偏远地区的库苏古尔湖中,碎片、纤维占微塑料总量的 60%[29]。在一些河流中,球形微塑料占主导地位,如在莱茵河中,球形颗粒占微塑料总量的 58.4%,粒径为300~1 000 μm[33]。在 20 世纪 70 年代,研究者就已发现淡水中的球形微塑料颗粒显示出与海洋中球形微塑料颗粒相似的特征,但淡水中球形颗粒的粒径明显小于后者[34]。在日本近海岸的淡水环境中,90%以上的球形微珠由 PE 组成[35]。

目前,在世界各地的淡水生态系统中均检测到了微塑料。在欧洲,英国泰马河中的微塑料平均含量为 1 m^3 0.028 particles[36]。在亚洲,中国长沙市内的 8 个湖泊中的微塑料含量为 1 m^3 2 425~7 050 particles[37]。中国湖北洪湖、洞庭湖、广东珠江、韩国洛东江的微塑料含量分别为 1 m^3 900~2 800 n、1 250~ 4 650 n、379~ 7 924 items、293~ 4 760 particles,而韩国洛东江和越南西贡河中的微塑料含量为 1 m^3 1.72×10^5~4.19×10^5 particles[38-41]。淡水环境中的微塑料含量和分布主要受到区域人口密度、地理位置、水文条件和气象环境等因素的影响。Wang 等[42]研究武汉市不同湖区的微塑料含量发现,位于人口密集的市中心的北湖和鲩子湖中的微塑料含量较高,分别为 1 m^3 8 925 items、8 550 items。类似的,德国莱茵河在鲁尔工业区段的微塑料含量较高,甚至达到峰值(1 km^2 3.90×10^7 particles)[33]。Fan 等[43]发现,珠江水域中微塑料的分布与当地人口密度及生产总值呈现明显的正相关关系。Xiong 等[44]发现,长江水域中的微塑料含量与水流流速呈负相关。Fischer 等[45]认为,博尔塞纳湖、丘西湖中微塑料的特征主要受到水循环的影响。位于瑞士的 Vuachere 河、Venoge 河中的微塑料含量在雨后显著增加,而处于城市地区的苏黎世湖、康斯坦斯湖水体经过强风造成的垂直混合后,湖中的微塑料含量反而降低,说明气象条件也是影响淡水环境中微塑料分布的重要因素[46]。

淡水环境中的沉积物也含有大量微塑料,它们作为研究微塑料污染的环境介质已被研究者广泛研究。结果表明,在瑞士的 6 个湖泊(日内瓦湖、康斯坦斯湖、马焦雷湖、苏黎世湖、纳沙泰尔湖和布里恩茨湖)的沉积物中,有不同类别和形状的微塑料,含量为 1 m^2 20~7 200 particles[46]。在德国莱茵河沉积物中,微塑料含量为 1 kg 228~3 763 particles,聚合物主要是 PE、PP 和聚苯乙烯(PS)颗粒,这 3 类聚合物的检出率达 75%以上[47]。微塑料在淡水沉积物中具有空间分布变化特征。意大利丘西湖东部沉积物中的微塑料含量显著高于西部(1 kg 266 particles与 205 particles)[45]。莱茵河干流和支流交汇处的沉积物中的微塑料含量高于交汇前的沉积物,可能由于受到汇集前后水流流速的影响,沉积物中微塑料的活化/固定效应有所不同[47]。Sarkar 等[48]发现,印度恒河沉积物中的微塑料含量与沉积物的磷酸盐含量、电导率呈显著相关关系,表明沉积物自身的理化特性也会影响其环境中的微塑料含量。综上,淡水系统作为微塑料进入海洋的运输路线,其水体中微塑料的分布仍需加以研究。

2.2 微塑料在海洋环境中的分布特征

纤维、碎片是海洋中最常见的微塑料类型,约占微塑料总量的 80%,远高于球状微塑料[49-50]。在地中海海水中,碎片微塑料含量为87.7%~93.2%,而球状微塑料含量仅为 2.0%[51]。纤维、碎片在海洋中的比例随空间变化而变化;在北极,纤维的含量最多(95.0%),其次是碎片(4.9%)[52];在地中海海洋,碎片的比例高达 93.2%[53]。通过鉴定聚合物类型可识别微塑料的来源,发现 PE、PP 和 PS 是全球地表水中最常报道的塑料碎片。Hidalgo-Ruz 等[9]发现,在海洋微塑料中,PE、PP 和 PS 类型占主导地位,这一结果与全球塑料生产类型基本一致。据统计,全球 62%的塑料制品生产原料来自 PE、PP[54]。

此外,在近海水域,聚对苯二甲酸乙二酯(PET)、合成橡胶、聚硬脂酸乙烯酯(PVS)、乙烯-醋酸乙烯酯(EVA)、环氧树脂、石蜡和聚己内酯(PCL)等的微塑料也已被发现[53]。人造丝(一种半合成纤维材料)、聚酯纤维(polyester)和尼龙(nylon)等半合成材料的微塑料可通过污水进入海洋环境,在海洋微塑料中占据不小的比例[50, 55]。

大多数塑料的密度低于海水,因而能在海水表面漂浮,使得海洋中的微塑料垃圾在海洋洋流的作用下实现远距离迁移。如西北太平洋海面的微塑料含量随着洋流的变化而变化,为 1 km^2 640~42 000 items[55],而阿拉伯湾海面的塑料含量则为 1 km^2 4.38×10^4~1.46×10^6 items[56]。由于大量接收来自周围陆地上的塑料垃圾,半封闭的地中海中也含有微塑料。Song 等[57]对韩国沿海区域的海水进行取样发现,微塑料在城市沿海地区的平均含量高达 1 m^3 1 051 particles,而农村沿海地区的微塑料含量只有 1 m^3 560 particles。Lacerda 等[58]在极地区域的表层水样中也发现了微塑料,其中在挪威斯瓦尔巴群岛南部、西南部测得的微塑料含量分别为 1 m^3 0~1.31 item、0~11.50 item。在格陵兰岛东北部海域,其微塑料含量达 1 $m^3$1~3 item[59]。而在南极周围海域,微塑料含量达到了 1 km^2 755~3 524 item[58]。

研究发现,海底沉积物中也含有大量微塑料,微塑料含量在海洋沉积物中主要受洋流速度、海底沉积物深度和距海岸线的距离等因素影响。Zhang 等[60]检测发现,微塑料在中国黄海及东海沉积物中的平均含量(干质量)分别为 1 kg 155 items、142 items,而远离海岸水域沉积物中微塑料含量(1 kg 60~90 items)远低于近岸海域沉积物中微塑料含量(1 kg 210~240 items)。在一项对白令海北部、楚科奇海的海底沉积物微塑料的监测中发现,微塑料的最高含量为 1 kg 68.9 items[61]。Li 等[62]发现,广西茅尾海入河口沉积物中的微塑料含量(1 kg 1 780~2 310 items)远高于河口区(1 kg 520~940 items),认为入口区较低的水流速度有利于微塑料向水底沉积。Wang 等[63]研究发现,在黄海南部水域,在0~20.0 m、20.1~40.0 m、40.1~60.0 m、60.1~80.0 m 沉积物中的微塑料含量分别为 1 kg 1 765.0 items、2 135.0 items、2 346.7 items、2 771.3 items,表明该水域沉积物中微塑料的含量与深度呈显著正相关。微塑料在全球水域的分布情况见表 1。

总体看出,水环境中微塑料类型的变化、分布特征可为微塑料溯源提供有用信息,有助于改善人们当前的塑料垃圾管理策略。

3　微塑料在水环境中的迁移特征

在水环境中,水域面积、深度、风向、水流速度和微塑料颗粒密度是决定微塑料迁移的重要因素[45]。大多数微塑料的密度低于淡水、海水的密度,因此微塑料往往浮于水面,沿着河流汇入海洋[7](图 1)。Besseling 等[64]研究了从毫米至纳米尺寸的球形颗粒(100 nm~10 mm)在淡水环境中的迁移形式,发现纳米塑料、微塑料的 99%保留率距离(99% retentiondistance,RD99)分别为 200 km、900 km,表明中等大小的微塑料向下游迁移的速度最快。通常情况下,微塑料尺寸越大,越容易在水体最上层漂移,此时,这种微塑料受地表水风浪引起漂移的影响较小,更有可能被带到近海[65]。此外,上层水体中的湍流会垂直混合漂浮状态的微塑料,使得微塑料在水柱中进行垂直迁移。Rezania 等[66]发现,上升速度较低的微塑料更易受到垂直迁移的影响。由于对微塑料垂直迁移的研究高度依赖于观测情况,使得多级塑料样品技术的分辨率较低,微塑料的垂直迁移研究仍有待完善。

在海洋中,生物淤积会明显影响微塑料的浮力(图 1)。生物淤积会增加微塑料的密度,形成中性浮力或负浮力,导致微塑料持续沉降。Kooi 等[67]预测,在生物淤积作用下,海洋中微塑料的垂直迁移与其大小有关,从而导致中间深度海水中的微塑料含量达到最大值,这一现象还会导致海面微塑料含量降低,从而使微塑料不会很快堆积在海床上。由于浮游动物有昼夜垂直迁移的生物习性,这大大增加了其与不同垂直深度微塑料接触的概率。浮游动物在选择性摄食过程中有可能会摄取附着有机物的微塑料,但不会消耗微塑料,在一定程度上起到了去污作用。

微塑料被水生生物摄食也是其在水环境中迁移的方式之一。有研究发现,尺寸较小的微塑料可被桡足类水生生物摄食,首先聚集于水生生物前中肠内,最终以密集堆积的粪便颗粒形式排出体外[8]。Vroom 等[68]发现,1 种桡足类动物(*Calanus finmarchicus*)肠道内的 PS 形成了聚集体,这个聚集体占整

个肠道体积的30%~90%,含微塑料的粪便颗粒被排出体外,加上水生动物的昼夜垂直迁移,微塑料会被运到更深的水域。粪便颗粒是其他海洋生物的食物来源,对悬浮有机物的垂直通量产生影响。但是粪便颗粒的微塑料密度较低、下沉慢,有可能对深海碳固存产生不利影响[69]。

表 1 微塑料在全球水域的分布

Table 1 Distribution of microplastics in global aquatic environment

水系	水体名称	出现频率(%)	含量	粒径	形状	成分	参考文献
淡水系统	美国五大湖	95.2	43 157 particles(1 km^2)	0.355~0.999 mm(81%)、1.000~4.749 mm(17%)、>4.750 mm(2%)	微珠	PE	[70]
	美国切萨皮克湾河口	98.0	297 927 particles(1 km^2)	0.3~2.0 mm	碎片、薄片、纤维	PE	[5]
	蒙古库苏古尔湖	100.0	20 264 particles(1 km^2)	0.355~0.999 mm(41%)、1.000~4.749 mm(40%)、>4.750 mm(19%)	碎片(40%)、薄片(38%)、纤维(20%)、球状(1%)		[29]
	瑞士六湖	100.0	91 000 particles(1 km^2)	<1 mm(85%)	碎片(61%)、纤维(10%)、球状(1%)	PE、PP、PS	[46]
	中国黄河		497~930 item(1 L)	<200 μm(87.94%)	碎片(2.14%)、纤维(93.12%)、其他(4.76%)	PE、PP、PS	[31]
	中国长江	100.0	8.47×10^6 particles(1 km^2)	0.5~1.6 mm(30%~57%)	碎片、纤维、薄片	PP、PE、PS	[71]
	中国太湖		6.8×10^6 particles(1 km^2)	0.333~1.000 mm	纤维(>60%)	PET、PS、PP	[30]
	中国珠江	95.4	0.688~8.211 n(1 m^3)	0.355~5.000 mm	碎片(39.0%)、薄片(22.0%)、泡沫(21.1%)	PE、PP、PS	[32]
	莱茵河德国段	100.0	892 777 particles(1 km^2)	300 μm~5 mm	碎片(37.5%)、纤维(2.5%)、球状(58.4%)	PS、PP、PVC	[33]
	韩国洛东江		293~4 760 particles(1 m^3)	<300 μm(74%)	碎片(69%)、纤维(30%)、薄片(1%)	PP、Polyester	[40]
	伊朗北部湿地		0.19~4.41 items(1 m^3)	1~2 mm	纤维	PE、PP	[72]
海洋系统	北极(海水)	93.0~95.0	0.34~2.86 particles(1 m^3)	0.25~7.71 mm	纤维(95.0%)、碎片(4.9%)	PE、Polyester、Nylon、Rayon	[52]
	北极(海冰)		38~234 particles(1 m^3)	2 mm	纤维	PE、PP、PS、Polyester、Nylon、Rayon	[55]
	大西洋	94.0	2.46~2.43 particles(1 m^3)	<5 mm(89%)	纤维(95.90%)、碎片(3.86%)	Polyester、Nylon	[50]
	太平洋东北部		8~9 180 particles(1 m^3)	0.1~1.0 mm(79.20%)、<0.1 mm(5.92%)、>1.0 mm(14.90%)	纤维(75.00%)		[49]
	大西洋(葡萄牙南部)	56.0			微纤维(80.6%)、碎片(19.4%)	Rayon、PP	[73]
	地中海	100.0	1.25 particles(1 m^3)	<300 μm(26.0%)、<500 μm(51.0%)、>5 mm(1.4%)	碎片(93.2%)、球状(2.2%)	PE、PP	[74]

PE:聚乙烯;PP:聚丙烯;PS:聚苯乙烯;PVC:聚氯乙烯;Rayon:人造丝;Polyester:聚酯纤维;Nylon:尼龙。粒径括号内的数据表示该粒径的检出频率;形状括号内的数据表示该形状的检出频率。

4 微塑料对水生动物的危害

自从人们发现微塑料在水环境中普遍存在以来,微塑料对水生动物的影响也逐渐引起全球研究人员的关注[75-77]。目前的研究结果表明,微塑料通过动物的摄食影响浮游动物、鱼类的生理健康,并通过食物链传播的方式威胁海龟、海鸟、鲸目动物和人类的健康。

目前已经发表的关于全球海洋中各种海洋生物摄入微塑料的研究结果表明,微塑料的摄入可在种群、个体、组织、器官、细胞和分子水平上影响水生生物的生理健康[78]。在个体和种群水平上,微塑料对生物体的健康产生有害影响,它们可能导致生物生殖健康水平下降,喂养能力受损,并最终导致生物死亡[79]。在组织和器官水平上,微塑料的摄入会导致发育中的斑马鱼(*Danio rerio*)肝脏产生病理应激和

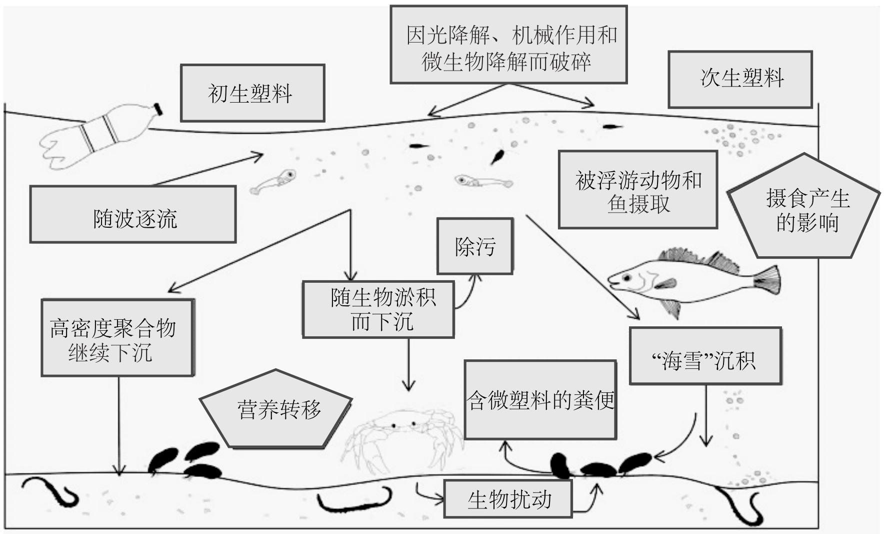

图 1　微塑料在水生态系统中的迁移(改自 Wright 等[68])

Fig.1　Transport of microplastics in aquatic environment (revised from Wright et al.[68])

组织损伤[80]。在细胞和分子水平上,摄入微塑料可导致氧化应激、能量代谢下降、免疫受损、神经传递功能障碍甚至基因毒性等[81-83]。本项目组利用 RNA-seq 研究微塑料对斑马鱼肠道的影响时也发现,暴露于不同大小的微塑料环境中后,包括精氨酸和脯氨酸代谢、心肌收缩、心肌细胞肾上腺素能信号系统、氧化磷酸化和核糖体等 KEGG 通路差异表达基因显著富集,表明用微塑料处理后,斑马鱼存在潜在的健康风险。另有研究发现,海鱼(*Oryzias latipes*)摄取并富集微塑料上吸附的有毒化学物质后,会导致病理、氧化应激及肝脏炎症[84]。蠕虫摄入微塑料后,其免疫细胞的吞噬活性下降[85],并引起免疫功能紊乱。目前,大多数关于微塑料影响的报道都集中在海洋环境、海洋生物上,关于微塑料对淡水生物的影响仍缺乏研究[86]。然而,淡水、陆地生物圈中都普遍存在着微塑料,有必要进一步研究微塑料对淡水生物的影响[87]。

由于微塑料的体积小,可以通过直接摄食、过滤摄食、悬浮摄食和食物链传播等方式被各种类型的生物摄入[88-89],如浮游动物[90-92]、海鸟[93]、鲸目动物[94]等。摄入微塑料会影响动物的生长发育、种群增长、免疫和激素系统、代谢和行为等,甚至会导致死亡[95]。据报道,摄入微塑料会在发育的斑马鱼肝脏中造成病理应激和组织损伤[96]。在营养转移过程中,微塑料可以改变摄食[97]和游泳行为[98]。微塑料具有较高的稳定性,难以被生物体消化或降解,首先会在水生生物肠道内积累,造成物理损伤[99-100]。目前,肠道损伤已被发现是微塑料对许多生物体造成伤害的主要影响[101],同时肠道损伤会进一步削弱生物的摄食活动,导致群体、个体、组织、器官水平上的生理健康状况恶化[102]。本项目组利用 RNA-seq 研究微塑料对斑马鱼肠道的影响时也发现,暴露于不同大小微塑料环境中后,包括精氨酸和脯氨酸代谢、心肌收缩、心肌细胞肾上腺素能信号、氧化磷酸化和核糖体等 KEGG 通路显著富集,相关基因显著上调表达,表明微塑料处理后斑马鱼存在潜在的健康风险[103]。其次,微塑料会沿着食物链从低营养水平的生物体转移到高营养水平的动物中[34],这种迁移方式会对人类健康产生威胁[90]。已有试验结果表明,微塑料可以在桡足类或多毛纲动物体内积累,也可以从贻贝转移到螃蟹中[104]。此外,微塑料还被证明可以通过其表面的有机污染物吸附功能,改变共暴露污染物的环境行为[105]。

5　结论与展望

水环境中的微塑料来源广泛,人类陆地活动是水环境中微塑料的主要来源,约占总量的 80%以上;碎片、纤维是水环境中最常见的微塑料形态,其中淡水中主要的微塑料类型是 PE、PP,海洋中的主要微塑料类型则是 PE、PP 和 PS。水环境中的微塑料含量、分布主要受到区域人口密度、地理位置、水文条件和气象环境等因素影响。微塑料在水系统表面、沉积物中均有分布,淡水系统是微塑料进入海洋

的主要运输路线;微塑料在海洋沉积物中的含量主要受洋流速度、海底沉积物深度和距海岸线的距离等因素影响。在水环境中,微塑料迁移主要受到水域面积、深度、风向、水流速度、微塑料颗粒密度、生物淤积和生物摄食的影响。

水生态系统中的微塑料会给水生动物带来不同程度的健康风险。微塑料可以通过直接或间接方式进入水生生物体内,导致群体、个体、组织、器官、细胞和分子水平上的生理健康损伤,并通过食物链传递的方式影响海龟、海鸟、鲸目动物及人类健康。微塑料作为塑料中主要的新型污染物,其主要源于人类活动产生的初级塑料、次级塑料,针对其污染特征开展系统性的治理工作已迫在眉睫。2021 年 9 月,中华人民共和国国家发展和改革委员会、中华人民共和国生态环境部联合印发了《"十四五"塑料污染治理行动方案》,其中明确提出,到 2025 年中国将有效落实塑料污染治理机制,对塑料制品进行全链条(生产加工、流通、消费、回收利用、末端处置)治理监控,实现有效遏制微塑料污染的绿色发展。

从当前大量关于微塑料产生源头及微塑料在淡水、海洋中迁移特征的研究结果看,今后在微塑料环境治理中,需要秉承全球一体化的思路,制定科学有效的治理方案,重视陆地中微塑料的流入,防范其生态危害与食物链渗透风险。下一步治理水环境中微塑料污染的研究方向应主要集中在以下几个方面:(1)微塑料污染源的深度解析及不同类型、性质微塑料的快速分离和鉴别技术;(2)气候变化、水动力等因素影响下微塑料在全球迁移中的变化情况;(3)结合微塑料污染特点,建立以科学分类、源头治理、迁移管控为主要内容的高效治理体系和监督机制等。

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