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玛瑙河多环境介质和铜锈环棱螺体内微塑料的赋存特征

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摘要: 微塑料污染对水生态系统及人类健康危害大, 为探究微塑料在不同环境介质中的赋存特征, 选择长江一级支流玛瑙河为研究区域, 通过现场采样、显微镜观察和傅里叶红外光谱测定等, 对玛瑙河表层水体、沉积物、河岸带土壤和底栖动物铜锈环棱螺中微塑料的丰度、粒径、形状、颜色和组成类型进行了分析。结果表明, 玛瑙河表层水体的微塑料平均丰度为 $(5.9 \pm 0.26) \text{ n} \cdot \text{L}^{-1}$; 上层沉积物中微塑料丰度(以干重计)为 $(1.35 \pm 0.1) \text{ n} \cdot \text{g}^{-1}$, 下层沉积物中微塑料丰度(以干重计)为 $(0.93 \pm 0.12) \text{ n} \cdot \text{g}^{-1}$; 近河岸带土壤中微塑料丰度(以干重计)为 $(0.68 \pm 0.16) \text{ n} \cdot \text{g}^{-1}$, 远河岸带土壤中微塑料丰度(以干重计)为 $(0.69 \pm 0.14) \text{ n} \cdot \text{g}^{-1}$; 铜锈环棱螺体内微塑料丰度为 $(2.06 \pm 0.25) \text{ n} \cdot \text{g}^{-1}$ 。分析发现, 上层沉积物和下层沉积物中微塑料丰度呈正相关; 铜锈环棱螺体内微塑料丰度分别与上、下层沉积物中微塑料丰度呈正相关; 近、远河岸带土壤中微塑料丰度具有相关性。各环境介质和铜锈环棱螺体内微塑料粒径大多 $< 0.1 \text{ mm}$, 主要形态为纤维状和碎片状, 颜色以蓝色和黑色为主, 成分主要是聚丙烯(PP)和聚乙烯(PE)。研究发现, 河岸带土壤中微塑料主要来源于农用塑料薄膜的破碎和分解。通过多环境介质调查和铜锈环棱螺体内微塑料的分析, 探明了大型底栖动物体内微塑料的累积效应, 可为全面了解微塑料潜在生态风险提供依据。

关键词: 微塑料; 沉积物; 河岸带; 铜锈环棱螺; 赋存特征

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Occurrence Characteristics of Microplastics in Multi-environmental Media and *Bellamya aeruginosa* of Manao River

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Abstract: Microplastic pollution poses threats to aquatic ecosystems and human health. In this study, in order to investigate the characteristics of microplastic occurrence in different environmental media, the abundance, particle size, shape, color, and composition types of microplastics in the water column, sediment, riparian zone soil, and the benthic snail *Bellamya aeruginosa* of the Manao River were analyzed using field sampling, microscopic observation, and Fourier infrared spectroscopy. The results showed that the average abundance of microplastics in the surface water of the Manao River was $(5.9 \pm 0.26) \text{ n} \cdot \text{L}^{-1}$; the abundance of microplastics in the upper sediment (by dry weight) was $(1.35 \pm 0.1) \text{ n} \cdot \text{g}^{-1}$, and that in the lower sediment (by dry weight) was $(0.93 \pm 0.12) \text{ n} \cdot \text{g}^{-1}$. The abundance of microplastics in the near riparian zone soil (by dry weight) was $(0.68 \pm 0.16) \text{ n} \cdot \text{g}^{-1}$, and that in the far riparian zone soil (by dry weight) was $(0.69 \pm 0.14) \text{ n} \cdot \text{g}^{-1}$, and the abundance of microplastics in the *B. aeruginosa* was $(2.06 \pm 0.25) \text{ n} \cdot \text{g}^{-1}$. The analysis results showed that the abundance of microplastics in the upper and lower sediments were positively correlated; the abundance of microplastics in *B. aeruginosa* was positively correlated with the abundance of microplastics in the upper and lower sediments, respectively; and the abundance of microplastics in the near and far riparian zone soils were also correlated. Most of the microplastics within each environmental medium and *B. aeruginosa* were $< 0.1 \text{ mm}$ in size, mainly in the form of fibers and fragments, mainly blue and black in color, and mainly composed of polypropylene (PP) and polyethylene (PE). It was found that microplastics in riparian zone soils mainly originated from the fragmentation and decomposition of agricultural plastic films. The results of this study shed light on the accumulation of microplastics in macrobenthic organisms through the investigation of microplastics in multi-environmental media and in the *B. aeruginosa*, which helps us to understand the potential ecological risk of microplastics in a comprehensive manner.

Key words: microplastics; sediment; riparian; *Bellamya aeruginosa*; distribution characteristics

塑料由于其优良的性能和低廉的价格而被广泛应用于人类生产生活中^[1]。2020年,全球塑料产量达到3.67亿t^[2]。废弃的塑料垃圾只有少部分被回收利用,大部分被焚烧或者填埋,在物理、化学和生物等作用下分解成粒径 $< 5 \text{ mm}$ 的塑料颗粒,即微塑料^[3]。相比塑料,微塑料粒径更小、数量更大且分布更广。由于微塑料具有吸附特性,重金属等污染物容易在其表面富集^[4]。微塑料的形态特征与某些生物的天然

猎物相似,可能被水生生物误食后损伤其消化道或器官,影响其生存和繁殖^[5]。

海洋被认为是微塑料最重要的汇,对微塑料的

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早期研究主要集中在海洋环境. 有研究表明, 微塑料会通过河流进入海洋, 加重海洋微塑料的污染^[6,7]; 与海洋相比, 淡水环境和土壤资源与人类生产和生活更加密切. 虽然近年来国内外学者对淡水环境中微塑料污染的研究逐渐增多, 但已有研究主要关注表层水体和沉积物中微塑料的分布特征, 如长江及其支流^[8,9]、城市河流^[10]和印度恒河^[11]等; 或者农田土壤中微塑料污染, 如汾河沿岸农田土壤^[12]和武汉潞水河不同土地利用类型土壤^[13]; 或者淡水生物体内微塑料污染, 如鄱阳湖铜锈环棱螺^[14]和桂林市淡水生物^[15]. 由于环境样本主要反映一个时间段的污染情况且微塑料可能在生物体内保留较长的时间, 因此生物体内微塑料可能会提供更多信息^[16]. 作为淡水环境分布最广泛和产量较高的底栖动物——铜锈环棱螺 (*Bellamya aeruginosa*) 是水生系统初级消费者的重要组成部分, 具有不可或缺的生态地位^[17]. 根据本课题组对玛瑙河长期监测的数据, 发现铜锈环棱螺是玛瑙河流域大型底栖动物的优势种. 故本研究结合玛瑙河流域不同环境介质中微塑料的污染水平, 以确定可能的微塑料风险.

众多学者探讨了长江干流及其支流水体中的微塑料赋存及空间分布, 而对水体、沉积物和河岸带土壤中微塑料的来源及迁移过程鲜有涉及. 基于此, 本文以长江中游北岸一级支流玛瑙河为研究区域, 根据微塑料在表层水体、沉积物和河岸带土壤这3种环境介质中的赋存特征、空间分布和污染现状, 分析了微塑料的污染行为和污染水平, 并探讨了沉积物中微塑料对大型底栖动物铜锈环棱螺体内微塑料积累的影响因素, 以期为进一步了解中小型河流微塑料的来源和迁移提供研究基础.

1 材料与方法

1.1 研究区域概况

玛瑙河位于湖北省宜昌市东南部, 属于长江中游北岸的一级支流, 总体流向由北向南. 本研究选取玛瑙河主河道(东经 111°28'~111°42', 北纬 30°23'~30°49')为研究区域; 流域面积 696 km², 年径流量 3.3×10⁸ m³·s⁻¹, 主河道长度 63.7 km, 坡降为 2.1%, 总体地势上游高下游低; 为季节性河流, 洪水多发于 6~8 月, 气候类型为亚热带季风气候, 气候温和湿润, 雨量充沛. 本研究选取玛瑙河主河道为研究区域(图 1).

1.2 样品采集

2022 年 4 月, 在玛瑙河干流共设置 8 个采样点位, 其中上游设置 2 个点位(M1、M2)、中游 3 个点位

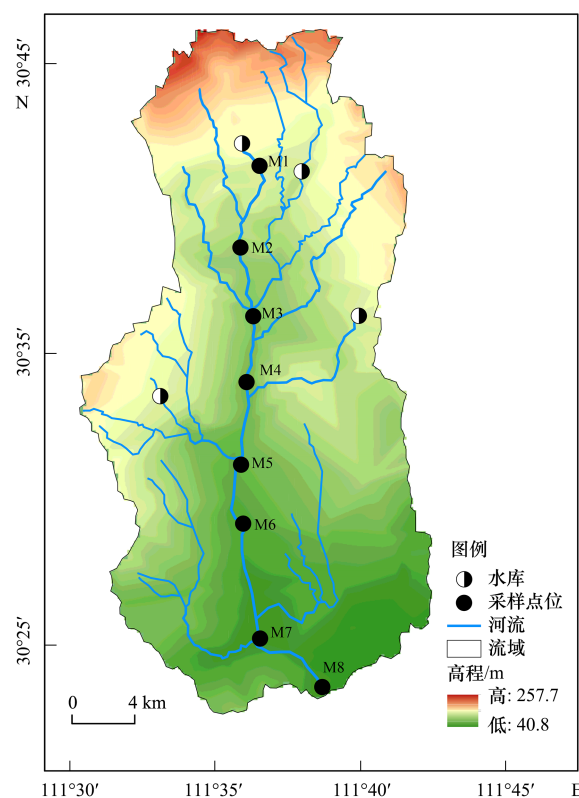


图 1 玛瑙河采样点位示意

Fig. 1 Location of sampling sites within Manao River

(M3~M5)和下游 3 个点位(M6~M8). 每个采样点位选择上下游可涉水河段 100 m 范围作为采样区域, 分别采集表层水体、沉积物、河岸带土壤和铜锈环棱螺 4 种样品. ①表层水体样品: 采用不锈钢采水器进行表层水体的采集, 每个样点分多次采集后注入 5 L 的透明玻璃水样瓶, 每个点位采集 3 份表层水体样品, 在当天运回实验室 4℃冰箱备用; ②沉积物样品: 采用不锈钢铲采集, 每个采样点位随机选取若干个 50 cm×50 cm 的正方形样方, 用不锈钢尺分割成 2 段泥块, 分为上层(0~3 cm)和下层(3~6 cm)沉积物样品. 每个点位采集 3 个平行样品, 用锡纸包裹后置于密封袋内保存, 并在当天运回实验室于 4℃冰箱中备用. ③河岸带土壤样品: 采用不锈钢铲采集, 沿水体至陆地方向设置近河岸带(距离水体 0~5 m)和远河岸带(距离水体 5~10 m), 随机采集土壤样品(每个点位采集 3 个平行样品), 充分混合后用锡纸包裹置于密封袋内保存, 并在当天运回实验室于 4℃冰箱备用. ④铜锈环棱螺样品: 采用不锈钢捞网采集, 每个点位设置 3 个采样组, 每个采样组随机采集 20 个样品. 样品用锡纸包裹后置于密封袋保存, 运回实验室后置于 -20℃冰箱中暂存备用.

采用 Hydro lab DS5 多参数水质分析仪(Hach, US)现场测定水体 pH、电导率(Cond)、溶解氧(DO)、

水温(T)等水体理化指标。

1.3 样品的分离与提取

表层水体样品: 将水样转移至烧杯, 加入适量 H_2O_2 溶液(30%)进行消解^[18], 并用纯水润洗过的玻璃棒搅拌 2 min 后, 用锡纸封口, 静置 12 h(消除有机质), 再使用玻璃棒充分搅拌后静置 12 h, 待充分消解后对样品进行抽滤, 滤膜选用 $\Phi 47\text{ mm} \times 10\text{ }\mu\text{m}$ 的玻璃纤维滤膜。抽滤后将滤膜置于直径 50 mm 的玻璃培养皿中风干备用, 贴标签待后续镜检。

沉积物、河岸带土壤样品: 将采集的样品置于 45℃ 的烘箱中烘干至恒重, 将烘干后的样品用不锈钢筛网(5 mm)过筛以除去砾石、贝壳等杂质。每个点位不同研究区域分别称取 100 g 样品(以干重计), 置于 1 L 烧杯中, 倒入 500 mL 饱和 NaCl 溶液($1.2\text{ g}\cdot\text{cm}^{-3}$)进行微塑料的浮选。使用玻璃棒充分搅拌, 锡纸封口后静置 6 h, 收集上清液于 2 L 烧杯中, 重复上述浮选过程 3 次^[8]。向收集的上清液加入 100 mL H_2O_2 溶液(30%)进行消解, 用镊子手工挑选可见的微塑料, 抽滤操作同水样的处理。

铜锈环棱螺样品: 处理前先用超纯水洗净铜锈环棱螺的外壳, 剖开软体部分, 用万分之一电子天平称重并记录。将样品置于 500 mL 烧杯中, 加入 30 mL 由 H_2O_2 (30%)和 HNO_3 (65%)配置成的混合溶液^[19], 其中 H_2O_2 与 HNO_3 的体积比为 1:3。用锡纸覆盖烧杯后置于恒温振荡箱中加热到 60℃ 恒温振荡, 直至软组织全部消解, 剩余的硝酸被蒸发掉^[14]。消解且冷却后向烧杯加入 500 mL 饱和 NaCl 溶液(密度为 $1.2\text{ g}\cdot\text{cm}^{-3}$)进行微塑料浮选, 用玻璃棒充分搅拌后静置 24 h。使用真空抽滤装置抽滤上清液, 滤膜的选用同水样。

1.4 微塑料的鉴定

将滤膜置于徕卡体式显微镜(Leica S9D, 美国)下观察微塑料的形状、颜色和粒径; 并挑选出塑料微粒或疑似塑料的微粒, 使用傅里叶红外光谱仪(PE·Fourier Transform, 美国)对挑选出的微粒进行成分鉴定, 根据吸收峰值判定其主要组成成分。

1.5 数据处理

利用 Excel 2016 统计数据; 利用 SPSS 26.0 进行相关性分析(皮尔逊检验); 利用 ArcGIS 10.8 软件绘制采样点位分布图; 利用 Origin 2021 绘制相关图表。

1.6 质量控制

为减少实验误差, 防止潜在的外源污染, 野外采样和实验室内微塑料的提取过程中均穿着纯棉衣服, 佩戴口罩和丁腈手套; 实验所用玻璃仪器和工具使用前均用纯水润洗 3 遍; 微塑料的分离和提取均在超净工作台上进行。

2 结果与分析

2.1 微塑料的丰度及分布特征

结果显示各采样点位微塑料的检出率达 100%。玛瑙河表层水体中微塑料丰度范围为 $2.15\sim 10.65\text{ n}\cdot\text{L}^{-1}$, 平均丰度为 $(5.9\pm 0.26)\text{ n}\cdot\text{L}^{-1}$ [图 2(c)]。入江口 M8 点丰度最低, 为 $2.15\text{ n}\cdot\text{L}^{-1}$; 丰度最高点出现在 M4 点, 高达 $10.65\text{ n}\cdot\text{L}^{-1}$, 约为 M8 的 5 倍。上层沉积物中微塑料丰度范围为 $0.45\sim 2.54\text{ n}\cdot\text{g}^{-1}$, 平均丰度为 $(1.35\pm 0.1)\text{ n}\cdot\text{g}^{-1}$; 下层沉积物微塑料丰度范围为 $0.19\sim 2.54\text{ n}\cdot\text{g}^{-1}$, 平均丰度为 $(0.93\pm 0.12)\text{ n}\cdot\text{g}^{-1}$; 上层沉积物和下层沉积物中微塑料丰度呈正相关($P<0.05$)。其中, 在所有沉积物样品中, M3 点的上层沉积物中微塑料丰度最高, 为 $(2.31\pm 0.16)\text{ n}\cdot\text{g}^{-1}$; M6 点的下层沉积物丰度最低, 为 $(0.2\pm 0.04)\text{ n}\cdot\text{g}^{-1}$ 。M4 和 M6 点间上、下层沉积物丰度差异最大。近河岸带土壤中微塑料丰度范围为 $0.31\sim 1.12\text{ n}\cdot\text{g}^{-1}$, 平均丰度为 $(0.68\pm 0.16)\text{ n}\cdot\text{g}^{-1}$; 远河岸带土壤微塑料丰度范围为 $0.4\sim 1.2\text{ n}\cdot\text{g}^{-1}$, 平均丰度为 $(0.69\pm 0.14)\text{ n}\cdot\text{g}^{-1}$ 。对近河岸带和远河岸带土壤微塑料丰度进行 Pearson 相关性分析, 结果显示存在显著正相关关系($P<0.05$)。在所有河岸带土壤样品中, M6 点的远河岸带土壤的微塑料丰度最高, 平均丰度为 $(1.3\pm 0.24)\text{ n}\cdot\text{g}^{-1}$ 。除 M3 点近河岸带土壤微塑料丰度为远河岸带土壤的 2 倍, 其余点位近、远土壤微塑料丰度差异不大。铜锈环棱螺体内微塑料丰度范围为 $0.95\sim 3.33\text{ n}\cdot\text{g}^{-1}$, 平均丰度为 $(2.06\pm 0.25)\text{ n}\cdot\text{g}^{-1}$ 。M3 和 M7 点间铜锈环棱螺体内微塑料丰度差异最大。

2.2 微塑料的分类特征

2.2.1 粒径特征

本文根据微塑料粒径划分为 4 类: $0\sim 0.1$ 、 $0.1\sim 0.5$ 、 $0.5\sim 1$ 和 $1\sim 5\text{ mm}$ ^[8]。在所有样品中, $< 0.1\text{ mm}$ 的微塑料最为丰富(图 3), 占全部样品的 63%~100%; 其次是 $0.1\sim 0.5\text{ mm}$, 占全部样品的 4%~30%。微塑料在玛瑙河干流各环境介质中表现出相同的分布特征, 丰度均随着粒径增大而减小。在各环境介质中微塑料的粒径大小分布为: 上层沉积物>下层沉积物>远河岸带土壤>近河岸带土壤>表层水体。

2.2.2 形状和颜色特征

玛瑙河表层水体、沉积物、河岸带和铜锈环棱螺样品中的微塑料在形态上主要分为 4 类: 碎片状、颗粒状、薄膜状和纤维状(图 4)。纤维状微塑料的粒径差异较大, 呈弯曲状态; 碎片状微塑料分为硬质塑料碎片和编织袋碎片; 颗粒状微塑料表面粗糙, 多为球

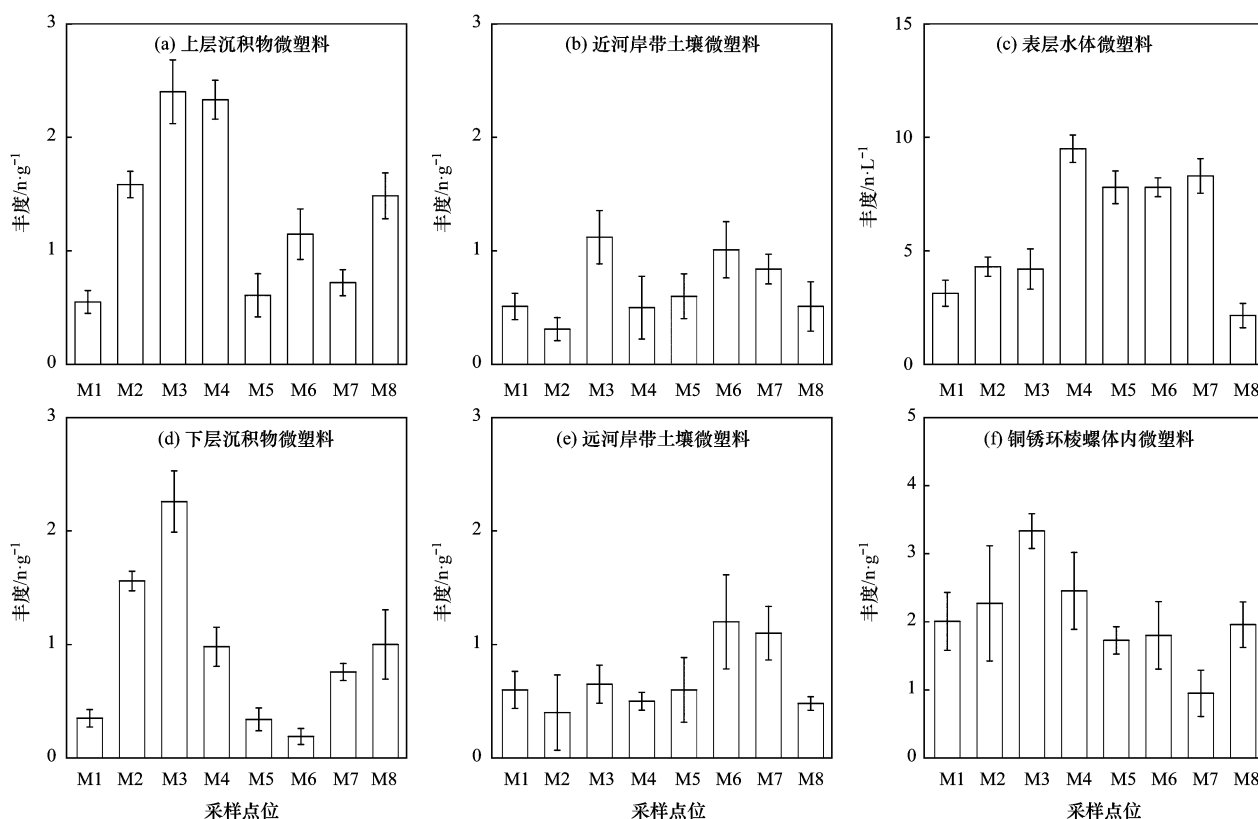


图2 玛瑙河流域微塑料丰度
Fig. 2 Abundance of microplastics in Manao River Basin

状或者卵球状;薄膜状微塑料质地柔软,多为轻薄透明的片状. 本研究中玛瑙河流域微塑料主要以纤维状和碎片状为主(图5),占比范围分别为5%~97%和3%~94%. 其中,碎片状微塑料在沉积物中所占比例高于水体;纤维状微塑料除了在沉积物中分布占比较少,在其余环境占比均较大.

各种各样的彩色塑料制品在现代生活中得到了广泛地应用,这些塑料制品在分解或裂解后产生了彩色塑料碎片. 玛瑙河微塑料总计发现蓝色、黑色、红色、白色、透明、彩色[多个颜色同时出现,图4(a)]和其他(紫色、绿色等)7类颜色,各颜色所占比例如表1所示. 表层水体、沉积物和河岸带土壤中微塑料主要颜色为蓝色和黑色,二者之和分别占样品总数的55%、76%和86%以上;彩色、紫色和绿色多出现于沉积物和河岸带样品.

2.2.3 类型

利用傅里叶红外光谱仪对聚合物进行鉴定,通过对官能团定性分析来确定样品的组成成分,典型红外光谱如图6所示. 玛瑙河干流流域微塑料共检测出6种类型,其中聚丙烯(PP,37.5%)、聚乙烯(PE,20%)和聚对苯二甲酸乙二醇酯(PET,12.5%)是主要的聚合物类型.

3 讨论

3.1 玛瑙河干流3种环境介质中微塑料的丰度、分布和特征

总体而言,玛瑙河各环境介质微塑料污染在天然淡水河道处于中等水平. 其中,表层水体微塑料污染低于香溪河流域^[8]同时期表层水体 $[(6.64 \pm 1.32) \text{ n} \cdot \text{L}^{-1}]$,高于渭河^[20]流域同时期表层水体 $[(5.8 \pm 1.6) \text{ n} \cdot \text{L}^{-1}]$. 沉积物微塑料丰度高于黄河三角洲湿地沉积物 $(20 \sim 520 \text{ n} \cdot \text{kg}^{-1})$,低于亚马逊河沉积物 $(0 \sim 5\,725 \text{ n} \cdot \text{kg}^{-1})$.

玛瑙河各采样点位间微塑料丰度差异明显,几乎所有位于人口密集区(M2、M5、M8)、农业种植区(M3~M8)和水产养殖区(M4、M6~M8)的微塑料丰度均高于河流平均值. 表层水体微塑料丰度总体呈现从上游到下游递增的趋势,M1点上游为白水水库,水库水体中的微塑料会沉积于底质中^[21],使得M1地表水的微塑料丰度降低,同时因为上游人口密度较低^[22],因此M1点微塑料丰度相对较低. 中下游段(M3~M7)表层水体微塑料污染较为严重,M2和M5点的下游均建有污水处理厂,有研究表明污水处理厂的尾水排放是水体微塑料的重要来源之一^[23],这可能是中下游段表层水体中微塑料污染较为严重的

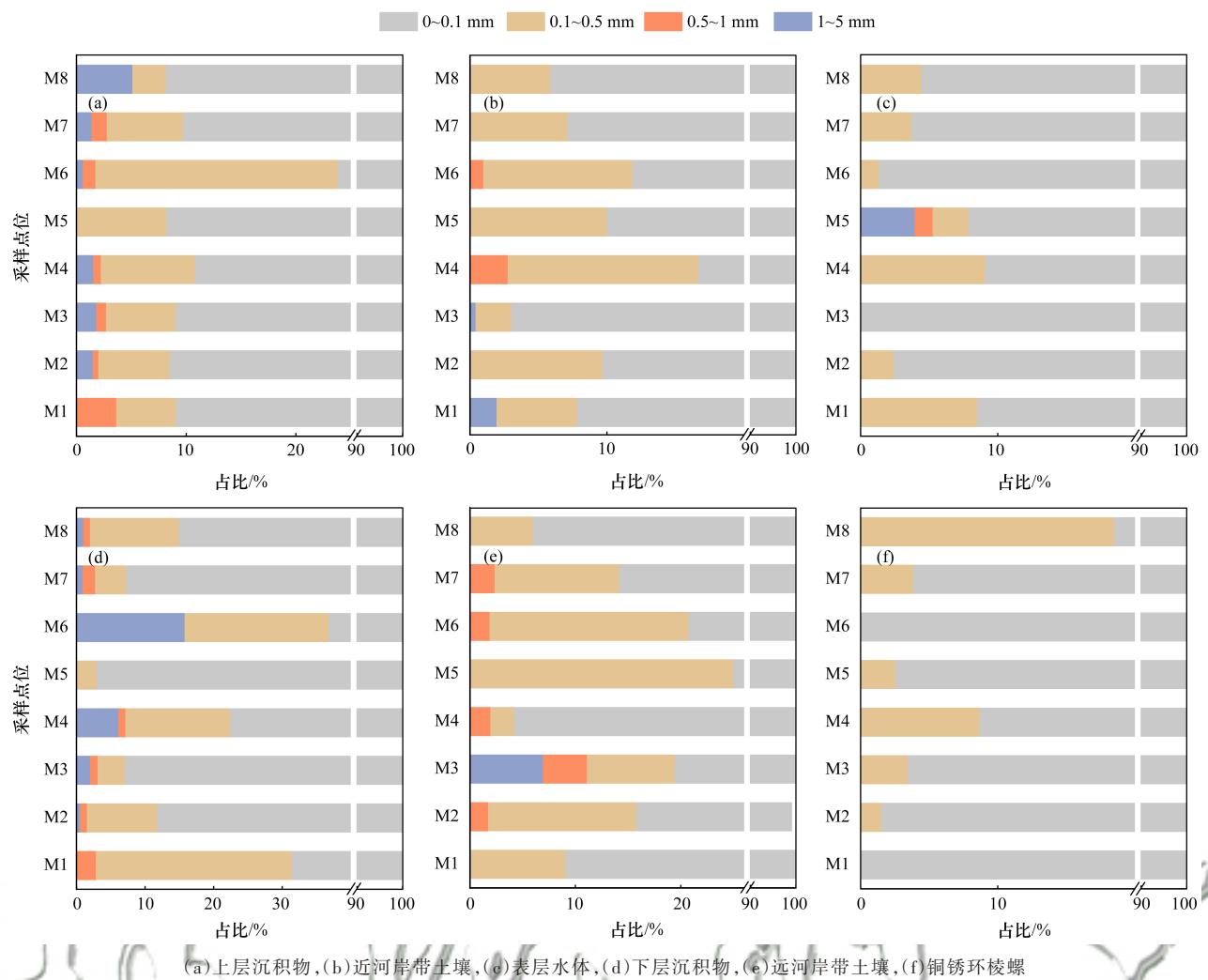
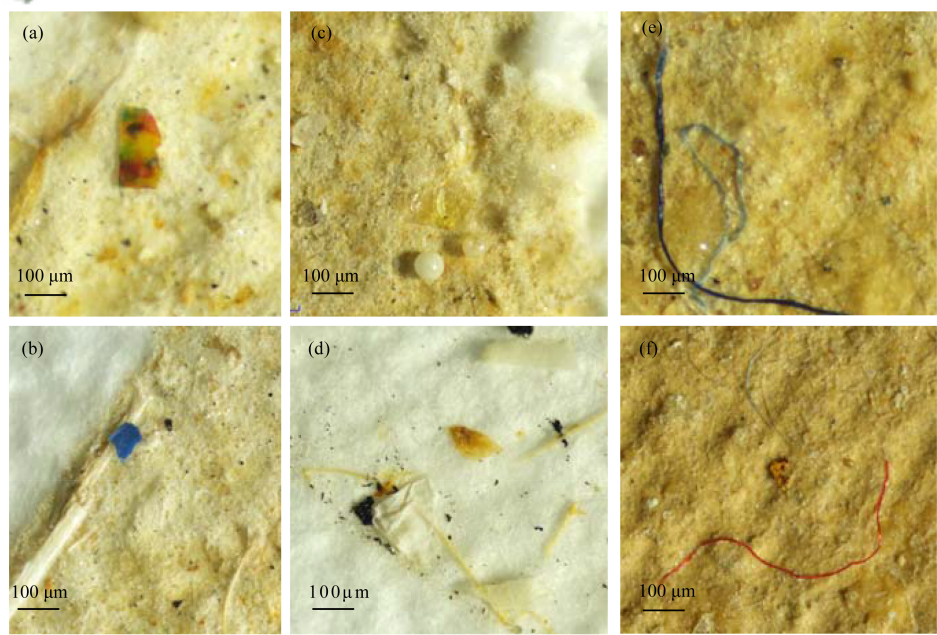


图3 玛瑙河流域不同环境中微塑料粒径分布特征

Fig. 3 Particle size distribution characteristics of microplastics in different environments of Manao River Basin



(a)和(b)碎片状;(c)颗粒状;(d)薄膜状;(e)和(f)纤维状

图4 玛瑙河流域不同形态的微塑料

Fig. 4 Shape of microplastic in Manao River Basin

表 1 不同环境中颜色分布占比/%

Table 1 Color of microplastics in different environments%

研究对象	蓝色	黑色	红色	白色	透明	彩色	其他
沉积物	37	18	17	3	2	12	10
河岸带土壤	44	32	10	2	2	4	6
表层水体	38	48	8	2	1	1	2
铜锈环棱螺	30	64	4	0	1	0	1

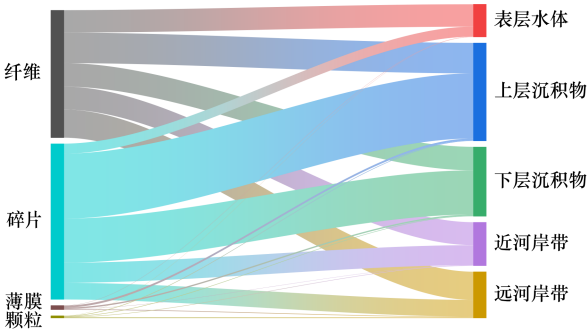


图 5 玛瑙河流域不同介质中微塑料形状分布特征

Fig. 5 Characteristics of microplastic shape distribution in different media of Manao River Basin

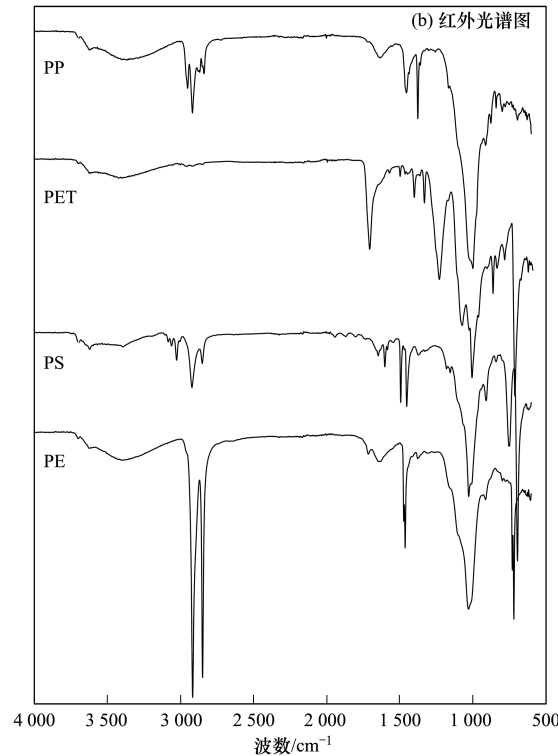
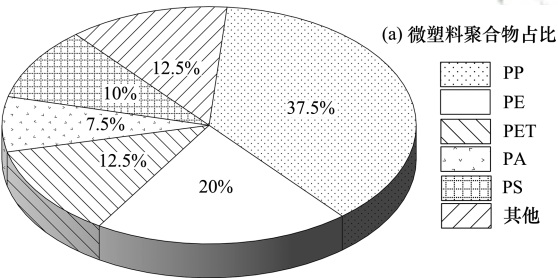


图 6 玛瑙河流域微塑料聚合物占比和红外光谱图

Fig. 6 Proportion of plastic polymers and infrared spectra of microplastics in Manao River Basin

主要原因. 下游段 M8 点在入江口附近, 由于该点水动力的冲刷作用较大, 导致 M8 点与其他点位在 3 种环境介质相比, 微塑料丰度偏低.

沉积物通常被认为是水生环境中微塑料的汇, 在深海沉积物^[24]和淡水沉积物^[25,26]中均检测到微塑料污染. 总体来说, 微塑料丰度随着沉积物深度的增加出现了下降的趋势. Pearson 相关性分析表明, 玛瑙河上层沉积物和下层沉积物中微塑料丰度呈显著正相关 ($P < 0.05$). 上层沉积物微塑料污染较为严重, 下层沉积物丰度略低于上层, 这可能是由于上层沉积物处于水相和固相之间不稳定的动态沉积环境^[27]. 玛瑙河 M2~M4 点沉积物微塑料丰度在所有点位中相对较高, M2 点位于城镇, 人口密度高且临近污水处理厂, 采样点位半径 1 km 内建有一座化工厂. 虽然排出的废水经过一系列处理后可以有效降低废水中微塑料的含量^[28], 但来自上游周边居民的生活污水和工农业产生的固体废物中夹杂的微塑料进入河流依然会导致 M2 点沉积物中微塑料丰度增加. 中游 M3 点地处三岔口断面的汇合点, 复杂的水动力特征可能导致沉积物中微塑料大量累积^[29]. 此外, M3 点沉积物分布的主要是碎片状微塑料, 其较高的密度和较小的比表面积等特性会使其更容易沉积^[30]. M5 采样点位区域河道变宽、水量升高, 其上、下层沉积物微塑料丰度骤降, 但表层水体丰度没有明显变化, 一方面可能是因为该点有支流汇入, 带入大量微塑料, 而同时河道变宽, 较大幅度地稀释了来自支流的微塑料; 另一方面可能是 M5 点沉积物分布的主要是纤维状微塑料, 不易沉积.

微塑料在土壤中会以水平和垂直方向运输, 包括生物和非生物运输. 微塑料通过农膜覆盖、废水灌溉、汽车轮胎磨损^[31]和大气沉降^[32]等途径进入远河岸带土壤中, 并在雨水冲刷、地表径流、耕作和生物扰动^[33]等作用下发生水平迁移后进入近河岸带土壤, 再通过近河岸带的雨水冲刷和水力冲刷作用反复淹没-出露-淹没, 进入水体. 其中一部分微塑料随水流流向下游、一部分被水生生物误食^[34]进入食物链等, 还有一部分由于自身重力等原因沉降在沉积物中, 此时沉积物成为玛瑙河干流微塑料的“汇”. 微塑料通过雨水淋溶^[35]、农业活动、生物扰动和干湿循环^[36]等途径垂向迁移进入土壤深层. 对各点位近河岸带和远河岸带土壤微塑料丰度进行 Pearson 相关性分析, 结果显示存在显著正相关关系 ($P < 0.05$). 此外, 流域的土地利用类型已被证明会影响河流中微塑料的丰度, 例如在法国艾因河^[37]和伊拉克阿尔万德河^[38]中, 流域的人口密度、土地利用和微塑料丰度之间有一定的关联. 玛瑙河流域工厂和居民区主要

分布在 M2、M5 和 M8 点位,而在以上点位的下游河岸带土壤中却发现了较高的微塑料污染,这可能由于工业废水和居民生活污水的排放造成了河岸带土壤的污染,从而影响土壤的肥力和结构,使得微塑料可以通过径流和生物扰动等方式进入下游河岸带土壤,并且工厂周边道路上频繁的汽车轮胎磨损运动^[39]产生的微塑料颗粒通过地表径流方式同样导致了下游点位较高的污染。

玛瑙河干流表层水体、沉积物和河岸带土壤的微塑料粒径以 $<0.1\text{ mm}$ 的微塑料为主,类似地,在草海湖地区的河口、湖泊和农田土壤3种环境中,粒径为 $0\sim 0.5\text{ mm}$ 的微塑料所占比例最大^[40]。Mason 等^[41]的研究表明,小粒径微塑料的大量存在可能与污水处理厂对小于 0.5 mm 微塑料的低去除率有关,并且从污水处理厂排出的微塑料随后在自然环境中不断被风化破碎成粒径更小的微塑料。此外,玛瑙河流域中微塑料在各环境介质中与其他物质的碰撞、磨损和风化的作用下会破碎成大量次级微塑料,这可能是小粒径微塑料在玛瑙河流域占比更高的一个重要原因。粒径为 $0.5\sim 1\text{ mm}$ 和 $1\sim 5\text{ mm}$ 的微塑料在上层沉积物、下层沉积物和远河岸带土壤中检测出的频率最高,而在近河岸带和表层水体的个别点位中也可以检测出。玛瑙河流域分布的微塑料主要是 PP 和 PE。PP 是一种热塑性塑料,具有优良的机械性能^[42],具有巨大的经济效益,被广泛用于工业;PE 无毒无味、韧性好、耐腐蚀,广泛用于各行业中,PP、PE 和聚苯乙烯(PS)的高工业相关性是它们大量存在的原因。此外,与高密度微塑料相比密度较低的聚丙烯($0.9\sim 0.91\text{ g}\cdot\text{cm}^{-3}$)和聚乙烯($0.917\sim 0.965\text{ g}\cdot\text{cm}^{-3}$),更容易漂浮在表层水体中,然而高密度的聚苯乙烯($1.04\sim 1.11\text{ g}\cdot\text{cm}^{-3}$)在表层水体样品中也检测出。这种现象表明,密度并不是影响微塑料分布的唯一因素,微塑料的垂直分布特征是外部环境和微塑料内在特性二者共同作用的结果^[43]。

3.2 铜锈环棱螺体内微塑料的积累

玛瑙河 8 个点位所采集的铜锈环棱螺体内微塑料丰度范围为 $0.95\sim 3.33\text{ n}\cdot\text{g}^{-1}$ 。对比鄱阳湖典型区的铜锈环棱螺^[14]微塑料丰度范围 $[(0.52\pm 0.15)\sim (2.48\pm 0.90)\text{ n}\cdot\text{g}^{-1}]$ 和鄱阳湖入湖段的中国圆田螺^[44]微塑料丰度范围($0.37\sim 1.42\text{ n}\cdot\text{g}^{-1}$),本研究铜锈环棱螺微塑料丰度相对较高;但丰度低于鄱阳湖入湖段的双壳类生物河蚬($2.92\sim 4.32\text{ n}\cdot\text{g}^{-1}$)^[44]和中国沿海水域的 9 种贝类($2.1\sim 10.5\text{ n}\cdot\text{g}^{-1}$)^[45]。本研究结果与其他地区的淡水底栖动物微塑料丰度相比,处于中等水平。

本研究中,铜锈环棱螺体内纤维状微塑料占比高达 97%,所摄取的颜色以蓝色和黑色为主,粒径主

要在 $<0.1\text{ mm}$ 范围内。泰国塔皮蓬杜昂河和班登湾贻贝和蛤蚶中纤维状微塑料占比高达 100% 和 95%,颜色以蓝色为主^[46]。中国黄海底栖动物^[47]中微塑料以纤维状为主,透明和黑色占比最高。本研究中铜锈环棱螺体内主要是纤维状微塑料,可能是因为具有柔韧性的纤维状微塑料更容易缠绕在铜锈环棱螺肠道或其他部位上,不易被生物排出,导致其体内纤维状微塑料的富集。Wang 等^[47]的研究发现,底栖动物对纤维状微塑料有相同的偏好,纤维是脊腹褐虾(*Crangon affinis*)、银锦蛤(*Acila mirabilis*)和萨氏真蛇尾(*Ophiura sarsii*)这 3 种底栖生物体内中最常见的形状。此外,An 等^[17]的研究表明铜锈环棱螺会利用其嗅觉和味觉受体将不可被消化的颗粒与食物区分开,但是不能过滤掉附着在食物上的微塑料颗粒;同样地,对海洋底栖生物厚壳玉黍螺(*Littorina littorea*)的研究发现,其不能区分附着在食物上的微塑料,导致微塑料的误食^[48]。

3.3 沉积物中微塑料对铜锈环棱螺的影响

有研究表明,水生生物体内微塑料丰度与水环境中微塑料的污染水平有关,前者可以间接反映后者的污染水平^[49]。Fernández^[50]的室内控制实验也证明了该观点,即在高浓度的微塑料中,贻贝对其吸收率增加。本研究铜锈环棱螺体内微塑料丰度与表层水体微塑料丰度之间没有显著相关性($P>0.05$),这可能是由于铜锈环棱螺主要生活在富含有机质的淤泥中,靠摄食沉积物中细微颗粒、有机碎屑和细菌生存繁衍^[51],因此主要摄取的是沉积物中的微塑料而不是漂浮在水体中的微塑料。Pearson 相关性分析表明,各点位铜锈环棱螺体内微塑料丰度与上层沉积物($P=0.017$)和下层沉积物($P=0.039$)微塑料丰度显著相关。江为群等^[14]在对鄱阳湖的研究中也发现环境中微塑料的含量越高,被铜锈环棱螺摄取的微塑料也越多。Silva 等^[52]的室内控制实验与本研究的结论一致,即大部分生活在沉积物中的底栖动物摄入了沉积物中的微塑料颗粒,并发现淡水沉积物中微塑料的存在会引起大型底栖无脊椎动物群落的变化。此外,底栖生物可以通过进食、挖洞等途径促进沉积物中微塑料的重新分布^[53,54];Nakki 等^[55]也发现生物扰动作用在将微塑料从沉积物表层纵向转移到沉积物深处起着重要作用。

沉积物是微塑料积累的汇和底栖动物的栖息地,且部分鱼类的主要猎物是底栖动物^[56],有毒的化学物质进入底栖动物后沿着食物链富集,对人类健康造成不利影响。此外,底栖动物可以通过进食微生物和生物扰动来影响环境的脱氮过程。Seeley 等^[57]研究发现微塑料会影响沉积物微生物群落的组成和功

能以及生物地球化学循环,比如由特定聚合物(如 PUF 和 PLA)分解的微塑料会增强沉积物的硝化和反硝化作用. Hope 等^[58]研究发现沉积物中纤维状微塑料降低了底栖微藻的生物量,改变了沉积物环境,并影响了沿海地区海洋沉积物的生物地球化学循环. 由于底栖动物通过食物网与沉积物中的微生物相互作用,导致微塑料可能会对营养级内和跨营养级食物网中底栖类群的丰度和多样性产生一定的影响^[59].

4 结论

(1) 玛瑙河干流普遍存在微塑料污染,表层水体中微塑料平均丰度为 $(5.9 \pm 0.26) \text{ n} \cdot \text{L}^{-1}$; 上层和下层沉积物微塑料丰度存在一定的相关性,丰度分别为 $(1.35 \pm 0.1) \text{ n} \cdot \text{g}^{-1}$ 和 $(0.93 \pm 0.12) \text{ n} \cdot \text{g}^{-1}$; 近河岸带和远河岸带微塑料丰度也存在一定的相关性,丰度分别为 $(0.68 \pm 0.16) \text{ n} \cdot \text{g}^{-1}$ 和 $(0.69 \pm 0.14) \text{ n} \cdot \text{g}^{-1}$.

(2) 微塑料尺寸越小丰度越高,玛瑙河各环境介质微塑料均以 $<0.1 \text{ mm}$ 为主; 颜色以蓝色、黑色为主; 形状以纤维状、碎片状为主,其聚合物类型主要为 PP 和 PE.

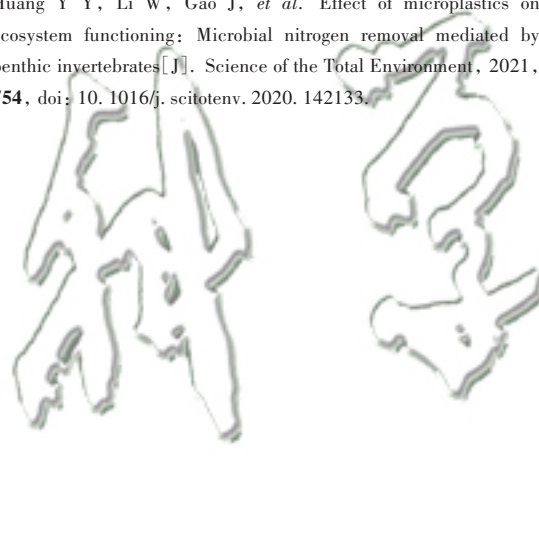
(3) 铜锈环棱螺体内微塑料丰度为 $(2.06 \pm 0.25) \text{ n} \cdot \text{g}^{-1}$, 各点位铜锈环棱螺体内微塑料丰度和上层、下层沉积物均存在相关性.

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