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长江流域微塑料污染特征及生态风险评价

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摘要: 长江作为我国第一大河流, 其流域微塑料污染状况尚未得到全面研究. 为此, 针对流域尺度建立微塑料综合调查评价体系, 以探明长江流域微塑料空间分布与组成特征, 解析其影响因素, 评价其生态风险. 结果表明, 研究区域微塑料丰度范围为 21~44 080 $\text{n}\cdot\text{m}^{-3}$, 平均丰度为 4 483 $\text{n}\cdot\text{m}^{-3}$. 在其空间分布上, 支流高于干流(赣江除外), 其中岷江流域成都段是微塑料检出丰度最高的支流地区. 流域微塑料尺寸集中在 0~1 mm, 形状以纤维和碎片为主, 颜色以彩色(有色)和透明为主. 进一步引入微塑料多样性指数, 发现辛普森指数和香农-维纳指数均能量化流域微塑料特征组成的多样性, 但二者变化趋势存在一定差别. 回归分析显示, 人类活动与微塑料丰度呈显著正相关($P<0.05$), 8 种人类活动因子中民用汽车保有量和旅游收入与微塑料丰度相关性最强, 说明交通运输业和旅游业是影响微塑料分布的主要因素. 从微塑料的潜在生态风险指数来看, 长江流域微塑料具有一定的生态风险, 68.97% 的区域属于Ⅲ级和Ⅳ级风险区, 其中太湖微塑料生态风险应受到更为广泛地关注.

关键词: 微塑料; 长江流域; 表层水体; 分布特征; 生态风险

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Pollution Characteristics and Ecological Risk Assessment of Microplastics in the Yangtze River Basin

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Abstract: The Yangtze River, the largest river in China, has not been comprehensively studied for its basin's microplastic pollution status. Therefore, a comprehensive investigation and assessment system of microplastics was developed at the river basin scale to characterize the spatial distribution and composition of microplastics in the Yangtze River Basin in order to analyze their influencing factors and assess their ecological risks. The results showed that the microplastic abundance in the study area ranged from 21 to 44 080 $\text{n}\cdot\text{m}^{-3}$, with an average abundance of 4 483 $\text{n}\cdot\text{m}^{-3}$. The spatial distribution of microplastic abundance was higher in the tributaries than in the main streams (except the Ganjiang Basin), with the Chengdu of the Minjiang Basin being the tributary area with the highest abundance of microplastics detected. The size of microplastics in the river basin was concentrated in the 0-1 mm range; the shapes were mainly fiber and fragment; and the colors were mainly colored and transparent. Further, introducing the diversity index of microplastics, it was found that both the Simpson index and the Shannon-Wiener index could quantify the diversity of microplastic characteristic composition in the river basin, but there were certain differences in the changing trends between the two. Regression analysis showed that anthropogenic activities were significantly and positively correlated with microplastic abundance ($P<0.05$), and among the eight anthropogenic activity factors, civilian vehicle ownership and tourism income were the most strongly correlated with microplastic abundance, indicating that transportation and tourism were the main factors influencing microplastic distribution. From the perspective of the potential ecological risk index of microplastics, microplastics in the Yangtze River Basin posed a certain ecological risk, with 68.97% of the area falling within risk zones III and IV, with the ecological risk of microplastics in Taihu Lake warranting more widespread attention.

Key words: microplastics; Yangtze River Basin; surface water; distribution characteristics; ecological risk

微塑料(microplastics, MPs)是指粒径小于 5 mm 的塑料颗粒、纤维或碎片. 早在 1972 年, 美国马尾藻海域就发现了其存在痕迹^[1], 但直到 2004 年这一概念才由 Thompson 在《科学》杂志上首次提出, 并自此成为国内外的研究热点^[2]. 微塑料来源于人们生产生活的方方面面, 陆地上沐浴露等个人护理品的使用^[3]、含纺织微纤维的废水排放^[4]、农田塑料薄膜的破碎^[5]、轮胎和道路标记的磨损^[6,7]、塑料垃圾的分解^[8]、海洋上的航海运输和水产养殖都会产生不同程度的微塑料污染^[9], 致使微塑料广泛存在于全球水环境中^[10]. 但微塑料自带毒性^[11]、难以降解、易被水生生物误食并沿食物链转移^[12], 从而影响生物正常的生长发育, 甚至可能威胁到人类健康^[13]. 更为复杂

的是, 微塑料聚合物类型发生变化时, 其对生物的毒性效应也随之改变, 杨柳等^[14]的研究表明与聚酰胺相比, 聚乙烯微塑料浸出液对生菜种子胚根和子叶的发育影响更大, 殷岑^[15]同样发现聚乙烯微塑料对斜生栅藻的生长抑制毒性大于聚氯乙烯.

长江是欧亚大陆上最大的河流, 同时也被认为是向海洋出口微塑料最多的河流^[16,17]. 自 Zhao 等^[18]于 2014 年第一次报道了长江口微塑料的污染现状, 长江流域微塑料研究进入了快速发展阶段, Su 等^[19]

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对长江中下游湖泊及长江口微塑料赋存情况进行调查, Wang等^[20]研究了长江城市(武汉)地表水中微塑料的污染情况, Xiong等^[21]聚焦于高原湖泊(青海湖)的微塑料污染特征. 然而大多数有以下3个限制: ①研究主要集中于干流或流域某一部分水体, 缺乏对全流域微塑料的整体性认识; ②微塑料特征组成的多样化与污染源数量存在联系^[22], 但没有统一的指标衡量长江流域微塑料特征组成的多样性; ③流域内的多个地区开展了微塑料生态风险评价, 但使用方法不一, 无法进行横向比较.

长江作为我国社会经济可持续发展的命脉和水资源配置的战略水源地, 其流域水生态环境状况直接关系到长江经济带的绿色发展和高质量发展. 因此, 本研究针对流域尺度建立了微塑料调查评价体系, 分析长江流域表层水体中微塑料污染特征, 引入多样性指数量化微塑料特征组成, 探究人为活动对流域微塑料的驱动机制, 评价水体微塑料的潜在生

态风险, 以期为长江流域微塑料污染防治提供科学依据并为其其他流域微塑料相关研究提供重要参考.

1 材料与方法

1.1 研究区域概况

长江发源于青藏高原, 向东于崇明岛汇入东海, 全长 6 300 km, 以宜昌和湖口为界分为上、中、下三段, 长度分别为 4 504、955 和 938 km(如图 1). 长江流域系指长江干支流的集水范围, 横跨我国三级阶梯, 面积约为 $1.8 \times 10^6 \text{ km}^2$, 占国土总面积的 18.8%. 流域内水系发达, 汇入的主要水系有雅砻江、岷江、嘉陵江、乌江、洞庭湖、汉江和鄱阳湖^[23]. 同时长江流域也被誉为我国的“黄金腰带”, 聚集了超过全国总量 40% 的人口和经济生产总值, 平均人口密度超过 $220 \text{ 人} \cdot \text{km}^{-2}$, 且呈现由西向东逐渐递增的规律, 其中长江三角洲地区是长江流域乃至全国人口最密集的地区.

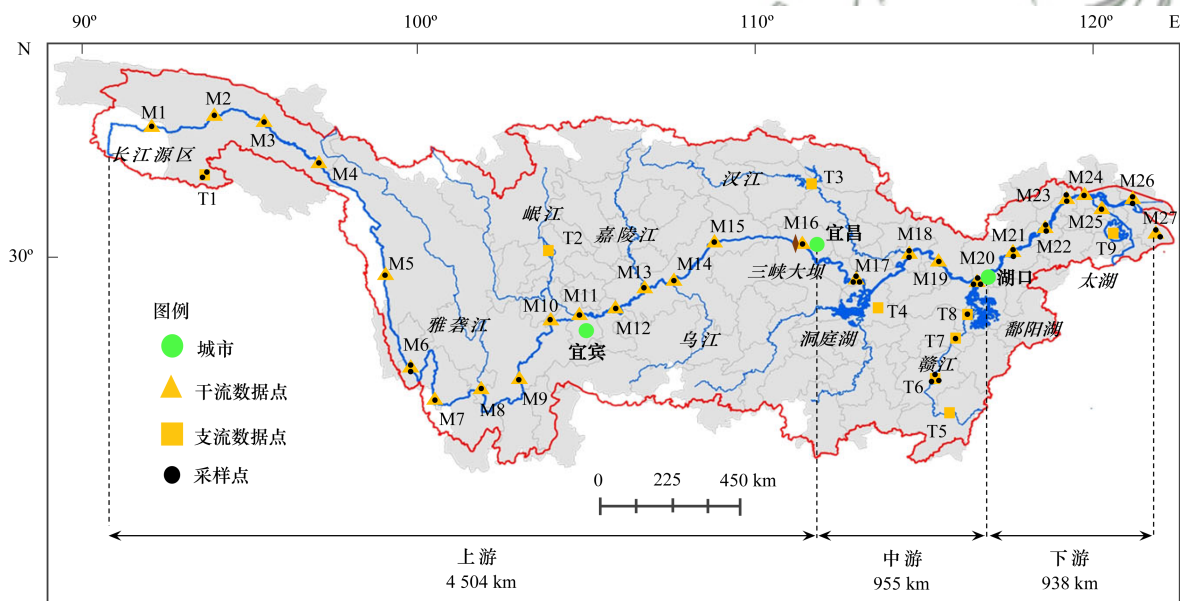


图 1 研究区域范围示意

Fig. 1 Schematic diagram of the study area scope

1.2 数据来源

(1)长江干支流的微塑料数据由既往研究提供, 其中长江源区^[24,25], 有 6 个采样点, 命名为 M1 ~ M4、T1-1 和 T1-2; 岷江流域成都段^[26]有 11 个采样点, 命名为 T2-1 ~ T2-11; 汉江流域丹江口段^[27]有 13 个采样点, 命名为 T3-1 ~ T3-13; 洞庭湖流域岳阳段^[28]有 14 个采样点, 命名为 T4-1 ~ T4-14; 赣江流域^[29]有 10 个采样点, 命名为 T5-1 ~ T5-5、T6、T7 和 T8; 太湖流域^[30]有 14 个采样点, 命名为 T9-1 ~ T9-14; 长江干流^[25]有 34 个采样点, 命名为 M5 ~ M27, 其中有两个及以上采样点的部分地区, 附加数字后缀加以区分. 微塑料数据的采样孔径处于 $10 \sim 75 \mu\text{m}$ 范围内, 时间范

围为 2019 年 8 月到 2020 年 1 月.

(2)收集微塑料采样点所在市级行政区的人类活动数据, 其中经济生产总值(gross domestic product, GDP, 亿元)、民用汽车保有量(万辆)、农林牧渔产值(亿元)和旅游收入(亿元)数据来自于各省统计年鉴以及地方国民经济和社会发展统计公报; 人口密度($\text{人} \cdot \text{km}^{-2}$)和城镇化率(%)数据来自于国家统计局发布的《第七次全国人口普查公报》; 工业废水排放量(万吨)数据来自于《中国城市统计年鉴》; 快递业务量(万件)来自于地方邮政管理局.

(3)水系和市级行政区划地理数据来源于国家地理信息公共服务平台(<https://www.tianditu.gov>).

cn/).

1.3 研究方法

1.3.1 微塑料多样性指数计算

为了分析研究区域中微塑料特征组成的复杂性,提出辛普森多样性指数(simpson diversity index, SDI)和香农-维纳指数(shannon-weiner index, SWI),两者都用于量化微塑料多样性,但前者对均匀度更加敏感,后者对丰富度更加敏感^[31,32]. 其计算公式如下:

$$SDI = 1 - \sum_{i=1}^S P_i^2 \tag{1}$$

$$\begin{cases} SWI = -\sum_{i=1}^S P_i \ln P_i, & P_i > 0, \\ SWI = -\sum_{i=1}^S P_i \ln (P_i + 1), & P_i = 0. \end{cases} \tag{2}$$

式中, S 表示类别数, P_i 表示类别*i*的微塑料在总样本中的比例.SDI最小值为0,最大值为1,且越接近1表示样本多样性越大.

1.3.2 微塑料生态风险计算

为了评价长江流域水体微塑料污染的生态风险,根据微塑料丰度和聚合物类型计算潜在生态风险指数(potential ecological risk index, PERI),计算公式如下:

$$\begin{cases} E_k = T_k \times \left(\frac{C_i}{C_0} \right), \\ T_k = P_k \times S_k, \\ PERI = \sum_{k=1}^m E_k. \end{cases} \tag{3}$$

式中, C_i 表示微塑料丰度; C_0 表示标准参考值,此处选择Everaert等^[33]计算出的表层水体中微塑料安全丰度($6\,650\text{ n}\cdot\text{m}^{-3}$); T_k 表示聚合物*k*的化学毒性系数; P_k 表示聚合物*k*的百分比; S_k 表示聚合物*k*的危害分数^[34],具体数值如表1所示,其中聚合物RA和PB根据其特性自定义危害分数; E_k 和PERI分别表示潜在生态风险因子和潜在生态风险指数. 潜在生态风险分级标准阈值分别为:Ⅰ($PERI<10$)、Ⅱ($10\leq PERI<100$)、Ⅲ($100\leq PERI<1\,000$)和Ⅳ($1\,000\leq PERI<10\,000$).

2 结果与讨论

2.1 长江流域水体微塑料空间分布

微塑料在长江流域表层水体中的丰度结果见图2. 结果表明,长江流域微塑料的丰度范围为 $21\sim 44\,080\text{ n}\cdot\text{m}^{-3}$,平均丰度为 $4\,483\text{ n}\cdot\text{m}^{-3}$. 除赣江之外,支流微塑料污染相比于干流更为严重. 这可能是因为支流作为微塑料污染的直接接纳水体,存在“二相性”,既是微塑料的“载体”同时也是微塑料的“汇”^[35],

表1 聚合物危害分数
Table 1 Polymer hazard fraction

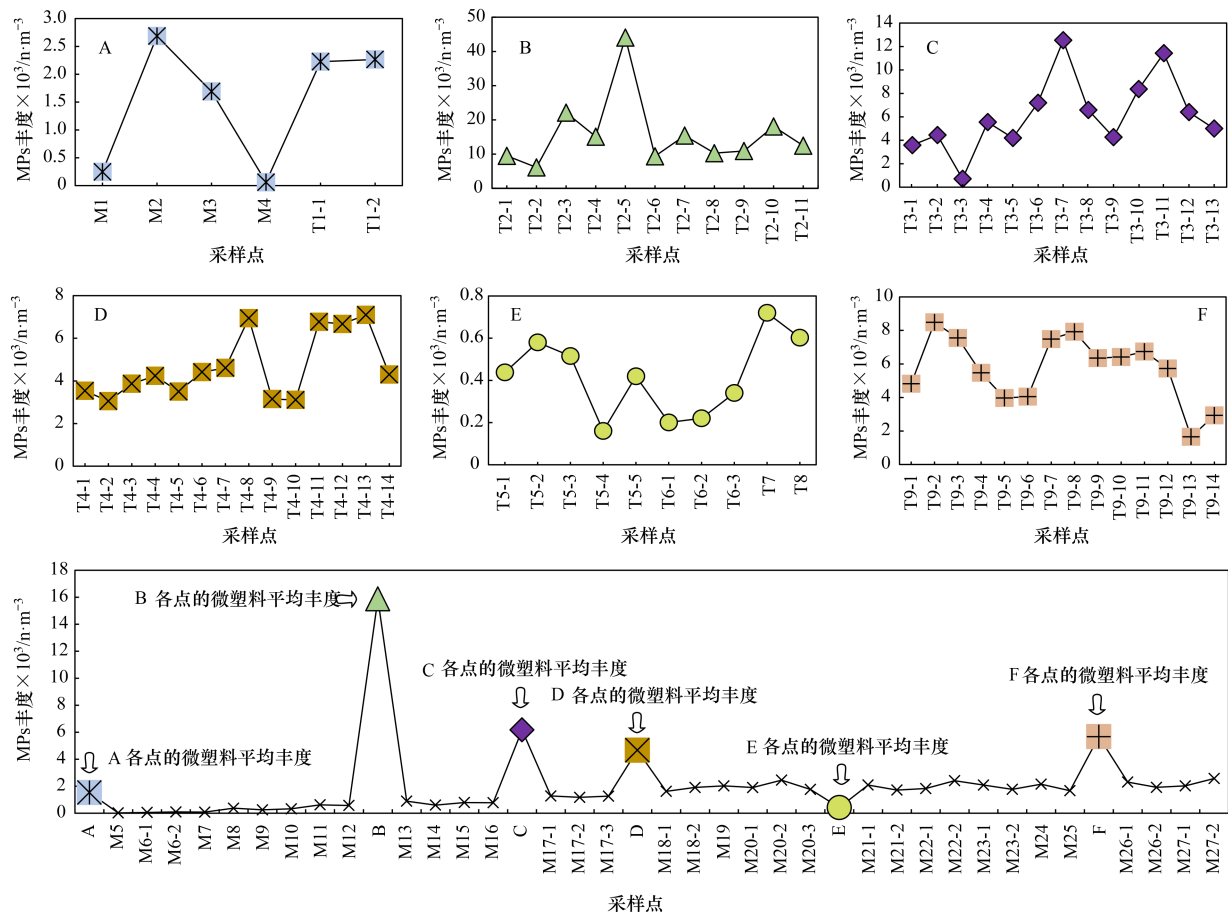
名称	缩写	危害分数 S_k (最高水平)
聚乙烯	PE	11
聚丙烯	PP	1
聚酰胺	PA	47
聚苯乙烯	PS	30
聚氯乙烯	PVC	10 551
人造丝	RA	1
聚氨酯	PU	7 384
聚对苯二甲酸乙二醇酯	PET	4
聚碳酸酯	PC	1 177
聚丁烯	PB	6
乙烯-醋酸乙烯共聚物	EVA	9

随着支流微塑料产生源与长江干流之间距离的增加,支流滞留效应凸显,微塑料在流域内部汇聚,从而加重支流微塑料污染. 此外,在支流中岷江流域是微塑料检出丰度的高值地区,范围为 $6\,110\sim 44\,080\text{ n}\cdot\text{m}^{-3}$,平均丰度高达 $15\,880\text{ n}\cdot\text{m}^{-3}$,与珠江($8\,725\sim 53\,250\text{ n}\cdot\text{m}^{-3}$)微塑料检出丰度相当^[35]. 究其原因,一方面采样区域流经中国西部最大城市和经济文化中心成都,2019年人口密度为 $1\,157\text{ 人}\cdot\text{km}^{-2}$,人均生产总值为10.34万元,分别为川渝平均水平的566%和168%^[36]. 人口密集、建筑面积大以及农业活动强度高原因进一步加剧了区域微塑料污染;另一方面成都地处四川盆地,近郊为西邻群山,冬季进入静稳气象状态后,垂直和水平扩散条件差容易造成微塑料等污染物的积累和滞留^[37],与成都地形相似的北方城市(北京),同样微塑料污染严重^[38].

有研究指出湖泊、水库等相对封闭或全封闭的水体,水文条件相对稳定,利于微塑料沉积与滞留,因而成为内陆水体中微塑料重要的“汇”^[39]. 本研究中丹江口水库($708\sim 12\,529\text{ n}\cdot\text{m}^{-3}$)、岳阳南湖($3\,050\sim 7\,100\text{ n}\cdot\text{m}^{-3}$)以及太湖($1\,650\sim 8\,480\text{ n}\cdot\text{m}^{-3}$)较高的微塑料丰度也印证了这一点. 但位于干流的三峡水库对微塑料的汇聚效应并不明显,微塑料丰度呈现自东向西逐渐增加的趋势,这可能是因为三峡水库属于典型的峡谷河道型水库^[40],而且采样时间处于水库的开闸补枯期,导致水流对微塑料的搬运作用较为强烈. Di等^[41]对三峡水库微塑料污染的调查同样表明,表层水体微塑料丰度与其距三峡大坝的距离无相关性,大坝并不具有明显的拦截作用.

2.2 长江流域水体微塑料特征组成

如图3所示,长江流域微塑料尺寸集中在 $0\sim 1\text{ mm}$,其中长江源区和太湖流域小于 0.5 mm 的占比高达96.46%和93.20%;形状以纤维和碎片为主,二者占比分别为54.63%和32.43%;颜色以彩色和透明为



采样点中A表示T1和M1~M4,B表示T2-1~T2-11,C表示T3-1~T3-13,D表示T4-1~T4-14,E表示T5-1~T5-8,F表示T9-1~T9-14

图2 长江流域微塑料丰度空间变化趋势

Fig. 2 Spatial variation trend of microplastic abundance in the Yangtze River Basin

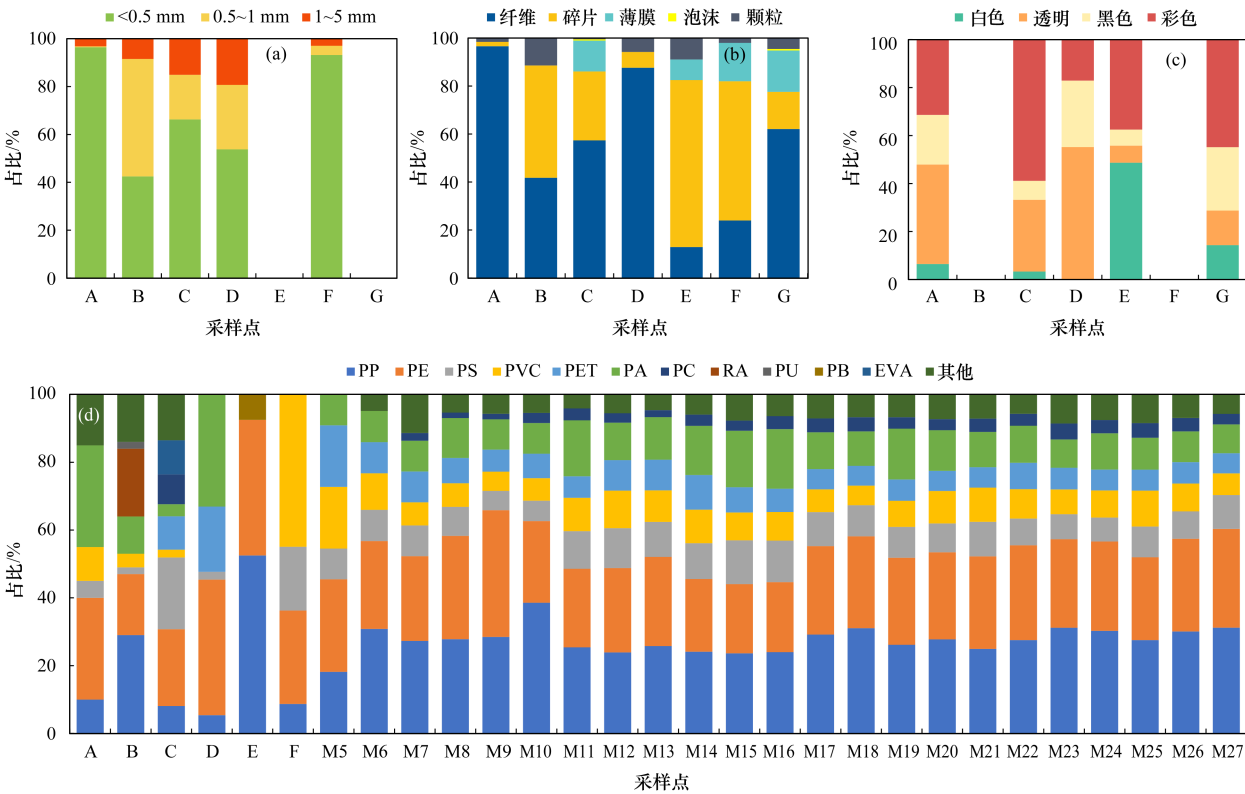
主,占比分别为237.93%和29.61%;聚合物类型中,PE和PP占比较大,分别为26.85%和25.80%。基于流域微塑料的特征组成,可以对其进行溯源分析,比如长江源区和洞庭湖岳阳段微塑料主导形状为纤维,主导颜色为透明,主导聚合物为PE和PA,推测区域微塑料与长江源区纺织品在建筑、装饰和服饰方面的广泛应用以及岳阳城区含洗衣纤维的生活污水排放有关^[42]。

目前微塑料分类还没有统一的标准,区域之间无法进行定量比较,因此利用SDI和SWI衡量长江流域微塑料在尺寸、颜色、形状和聚合物方面的多样性。微塑料尺寸、形状、颜色和聚合物的SDI多样性指数分别为0.462~0.607、0.067~0.593、0.557~0.688和0.558~0.882,SWI多样性指数分别为0.853~1.068、0.078~1.061、0.985~1.269和0.899~1.810(图4)。与以往的研究相比,本研究的SDI(0.586)高于贵州南明河流域微塑料的SDI(0.544)^[43],但SWI(1.087)小于莱州湾微塑料的SWI(1.840)^[44]。SWI和SDI在量化微塑料聚合物多样性方面变化趋势相同,但在尺寸、形状和颜色方面略有

差异,特别是在微塑料尺寸多样性中汉江流域丹江口段的SDI处于下降趋势但SWI却在上升,说明该区域微塑料尺寸的丰富度在增加但均匀度在减少。

2.3 流域微塑料赋存特征影响因素

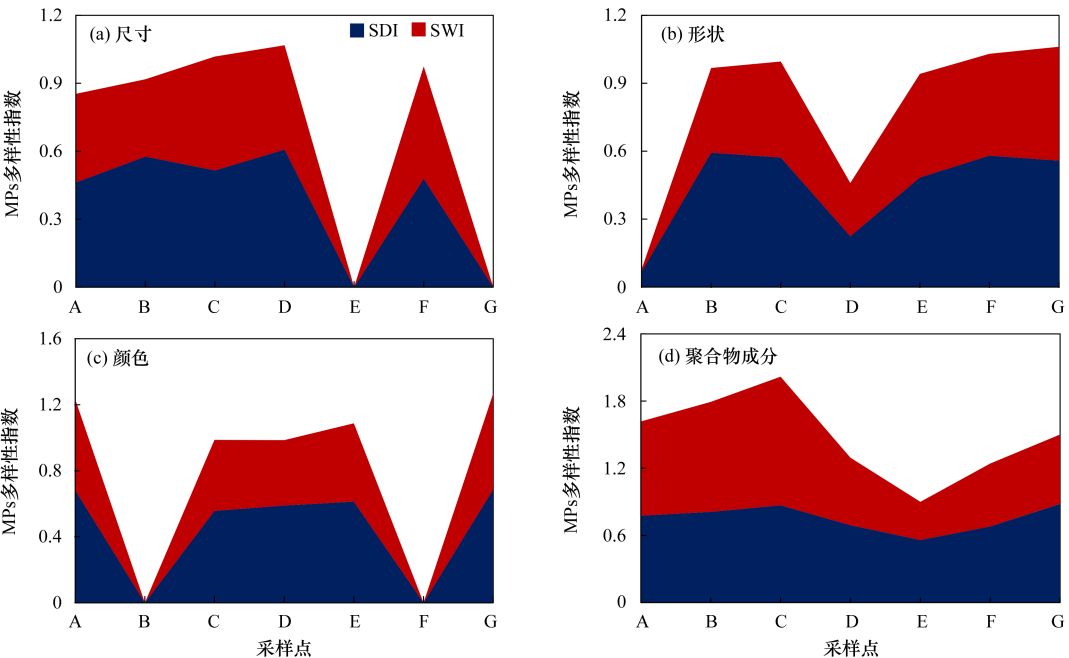
人类是微塑料的唯一来源^[45],直接影响着微塑料在环境中的分布情况。图5的回归分析表明,人类活动与微塑料丰度呈显著正相关($P<0.05$),其中民用汽车保有量和旅游收入与微塑料丰度相关性较强,城镇化率、快递业务量和GDP与微塑料丰度的相关性次之,人口密度、工业废水排放量和农林牧渔产值与微塑料丰度的相关性较弱,这说明了交通运输业和旅游业是影响微塑料分布的主要行业。汽车行驶过程中轮胎磨损产生的微塑料会通过道路径流或雨水径流进入水环境^[46],并已成为水体微塑料的最大来源^[47]。Kole等^[48]通过计算表明轮胎磨损微塑料的人均排放量达到了0.81 kg,一年的全球释放量高达591万t,同时汽车数量决定了轮胎磨损微塑料的释放量^[49],使得本研究中汽车保有量与微塑料丰度相关性最强。此外旅游收入与微塑料丰度同样具有较强相关性,造成这一现象的原因是游客产生的垃圾



(a) 尺寸, (b) 形状, (c) 颜色, (d) 聚合物成分; 采样点中 A 表示 T1 和 M1~M4, B 表示 T2-1~T2-11, C 表示 T3-1~T3-13, D 表示 T4-1~T4-14, E 表示 T5~T8, F 表示 T9-1~T9-14, G 表示 M5~M27; 部分采样点未对微塑料尺寸或颜色进行鉴定

图 3 长江流域微塑料的形态分布

Fig. 3 Morphological distribution of microplastics in the Yangtze River Basin



采样点中 A 表示 T1 和 M1~M4, B 表示 T2-1~T2-11, C 表示 T3-1~T3-13, D 表示 T4-1~T4-14, E 表示 T5~T8, F 表示 T9-1~T9-14, G 表示 M5~M27

图 4 长江流域微塑料多样性指数

Fig. 4 Microplastic diversity index in the Yangtze River Basin

中 44% 为塑料废弃物^[50], 而景区垃圾产生源分散且不易控制, 加之假期游客高峰期垃圾桶数量严重不足以及工作人员清洁不及时导致塑料废弃物管理不

善容易进入环境中, 进而造成水体微塑料污染。

让人意外的是, 人口密度和工业废水排放量与微塑料丰度相关性较弱, 这可能是因为污水处理厂

去除了生活污水及工业废水中的部分微塑料, Gao 等^[51]的调查表明污水处理厂对微塑料的去除率为 50%~99.99% 不等. 农林牧渔产值与微塑料丰度最弱, 说明农用塑料薄膜虽然是土壤微塑料的重要来

源^[52], 但可能会在土壤系统中滞留, 仅部分通过地表径流进入水体中. 王慧等^[53]在淮河流域开展的研究证实了这一点, 强降雨情况下表层土壤(10 cm)的农业源微塑料平均流失比例为 7.58%.

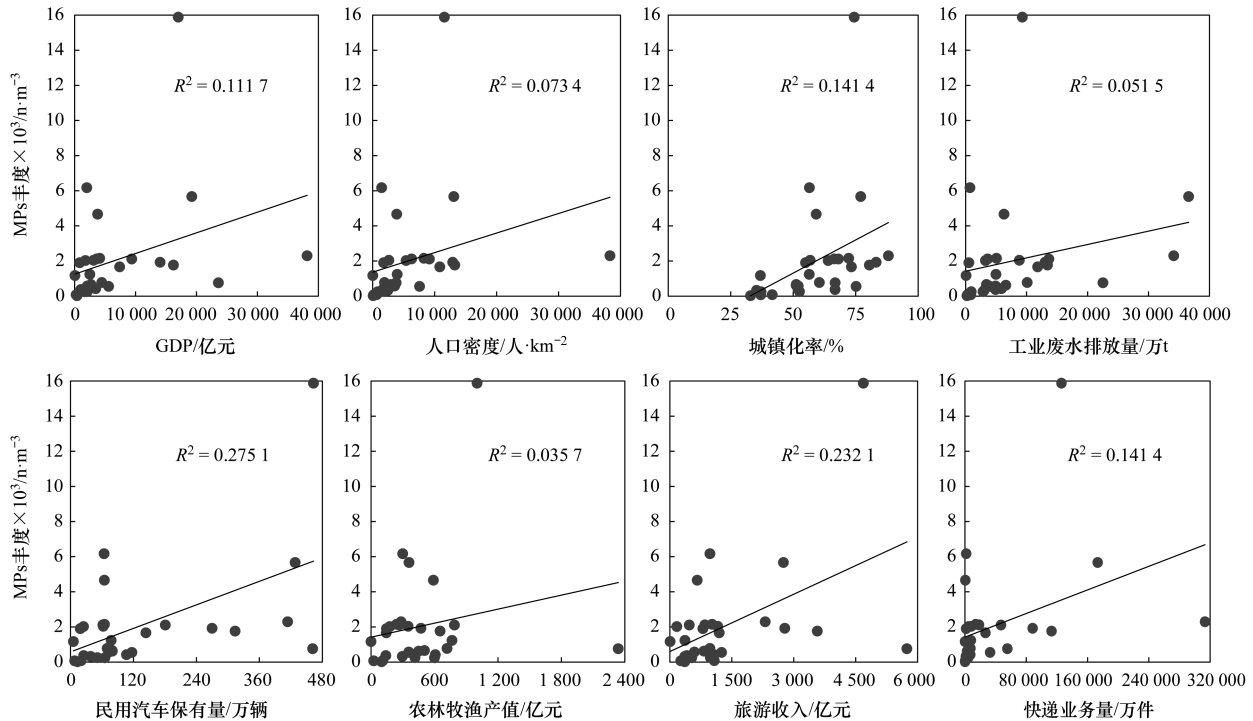


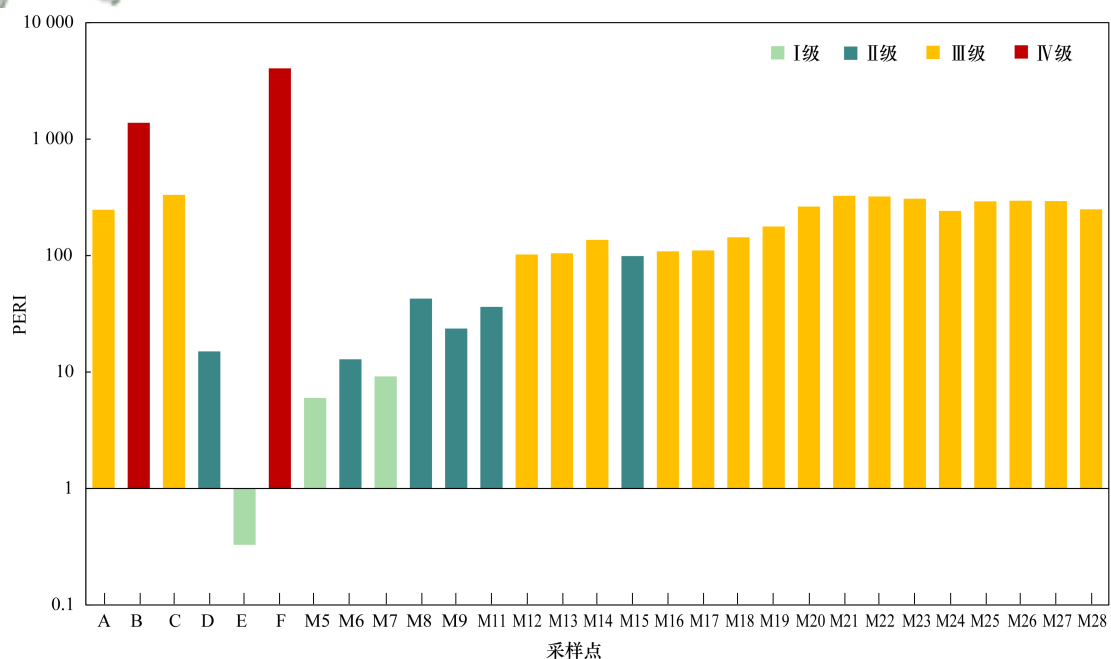
图5 长江流域微塑料丰度与人类活动的关系

Fig. 5 Relationship between microplastic abundance and anthropogenic activities in the Yangtze River Basin

2.4 长江流域微塑料生态风险评价

采用潜在生态风险指数法对长江流域水体微塑料污染造成的生态风险进行了评价(图6). 流域微塑料

料的 PERI 值差异巨大, 介于 0.33 ~ 4 049 之间, 就比例而言, 6.90% 的地区属于 IV 级风险区, 62.07% 的地区属于 III 级风险区, 20.69% 的地区属于 II 级风险区,



采样点中 A 表示 T1 和 M1~M4, B 表示 T2-1~T2-11, C 表示 T3-1~T3-13, D 表示 T4-1~T4-14, E 表示 T5~T8, F 表示 T9-1~T9-14

图6 长江流域微塑料潜在生态风险水平

Fig. 6 Potential ecological risk level of microplastics in the Yangtze River Basin

10.34%的地区属于Ⅰ级风险区。岷江流域成都段和太湖流域PERI值过高,导致流域整体微塑料生态风险高于西江主流区(PERI: 231~943)^[54]、泰国沿海省份(PERI: 50~470)^[55]以及印度海港城市(PERI: 253~445)^[56]水体中微塑料的生态风险,但显著低于我国海湾微塑料生态风险^[57]。

PERI值最高的地区出现在太湖流域,绝大部分由PVC贡献,占PERI值的99.81%。蓝藻水华等富营养化问题一直是太湖流域水污染防治的重点,而最新研究表明微塑料可能会改变有害蓝藻的分布^[58],本研究中太湖流域过高的微塑料生态风险可能会扩大有害蓝藻的发生区域和发生风险。进入干流后,PERI值的峰值为326,出现在长江中游和下游的分界线,PVC贡献了总PERI值的95.31%,同时该处也是鄱阳湖与长江的交汇处,水量交换频繁,微塑料也随之迁移。虽然鄱阳湖上游入湖河流——赣江的PERI值仅为0.33,但下游长江微塑料生态风险较高,可能会对鄱阳湖这类过水性、吞吐型湖泊的自然保护区以及敏感物种造成威胁。微塑料的生态风险由微塑料丰度和聚合物类型共同决定,在削减微塑料丰度的同时应注意PVC和PU等高风险聚合物的控制。

3 结论

(1) 长江流域微塑料分布具有明显的空间异质性,其丰度范围为21~44 080 n·m⁻³;支流微塑料污染相比于干流更为严重,且丰度最高值出现在岷江流域成都段;太湖、南湖和丹江口水库等湖泊、水库是微塑料重要的“汇”。目前研究侧重于长江流域微塑料的空间分布,未来将结合时间尺度进行深入探讨。

(2) 流域微塑料尺寸集中在0~1 mm,形状以纤维和碎片为主,颜色以彩色(有色)和透明为主,聚合物以PE和PP为主,用于衡量微塑料多样性的辛普森指数和香农-维纳指数空间变化趋势略有不同。

(3) 人类活动与微塑料丰度呈显著正相关($P < 0.05$),其中民用汽车保有量和旅游收入与微塑料丰度相关性最强,而污水处理厂的去除和土壤系统的滞留导致人口密度、工业废水排放量以及农林牧渔产值与水体中微塑料丰度的相关性较弱。

(4) 长江流域微塑料生态风险水平相对较高,68.97%的区域属于Ⅲ级和Ⅳ级风险区,最高值出现在太湖流域。此外,主要影响微塑料生态风险的聚合物类型为PVC和PU,因此在微塑料生态风险防控方面,应同时注意微塑料丰度削减与高风险聚合物控制。

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