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冠状病毒气溶胶传播及环境影响因素

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滇池近岸水体微塑料污染与富营养化的相关性

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摘要: 内陆淡水湖泊微塑料污染受到广泛关注, 但与水体富营养化的相关性尚不明确。在滇池沿岸布设 24 个采样点, 研究了近岸表层水体微塑料丰度、聚合物成分、粒径、颜色及形态, 同步测定富营养化相关水质指标并计算富营养化状态指数。结果表明, 滇池近岸水体微塑料丰度在 $800 \sim 6\,000 \text{ n} \cdot \text{m}^{-3}$ 之间, 平均为 $2\,867 \text{ n} \cdot \text{m}^{-3}$, 检出的聚合物类型主要是聚对苯二甲酸乙二醇酯 (polyethylene terephthalate, PET)、聚醚型聚氨酯 (polyetherurethane, PEU)、聚丙烯 (polypropylene, PP)、聚乙烯 (polyethylene, PE) 和聚醋酸乙烯酯 (polyvinyl acetate, PVAc)。微塑料粒径以 $0.2 \sim 0.5 \text{ mm}$ 为主, 纤维状微塑料是最主要的检出形态, 其次为碎片和薄膜。24 个监测点中, 处于重度、中度、轻度富营养化和中营养水平的样点数分别占 8.33%、58.33%、29.17% 和 4.17%, 主要污染物为总氮 (TN)。相关性分析发现滇池近岸水体微塑料丰度与 TN 质量浓度呈极显著正相关 ($P < 0.01$), 与叶绿素 a (Chl-a) 呈负相关, 但未达到显著性水平 ($P > 0.05$), 靠近昆明市主城区的北岸水体中微塑料丰度和 TN 质量浓度均显著高于其他三岸, 主要来源于污水处理厂尾水排放。

关键词: 微塑料; 滇池; 富营养化; 污染特征; 近岸水体

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Correlation Between Microplastics Pollution and Eutrophication in the Near Shore Waters of Dianchi Lake

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Abstract: Microplastics have been found in many environmental media such as sea water, coastal tidal flats, terrestrial water, sediments, and organisms. Microplastics pollution in inland freshwater lakes have received extensive attention; however, the correlation between eutrophication and microplastics pollution in freshwater lakes remains unclear. In this study, 24 sampling sites were set up in the near shore surface waters of Dianchi Lake, and the pollution characteristics of microplastics such as abundance, composition, particle size, color, and form were evaluated. Water quality parameters related to eutrophication state were analyzed, and the eutrophication indices were further calculated. Specifically, sample pre-treatment was conducted according to the method issued by National Oceanic and Atmospheric Administration (NOAA) of the United States. The color and morphological characteristics of microplastic samples were observed using a stereoscopic microscope, and counts and particle size measurements were performed using Nano Measure 1.2 software. Parts of the samples were selected, and the polymer composition analysis was performed using micro-Fourier Transform infrared (μ -FTIR) spectroscopy. The indices related to eutrophication level evaluation were tested according to the experimental standard methods issued by the Ministry of Ecology and Environment of China. The results showed that the abundance of microplastics in the near shore waters of Dianchi Lake was between 800 and $6\,000 \text{ n} \cdot \text{m}^{-3}$, with an average value of $2\,867 \text{ n} \cdot \text{m}^{-3}$. The types of polymers detected were polyethylene terephthalate (PET), polyetherurethane (PEU), polypropylene (PP), polyethylene (PE), and polyvinyl acetate (PVAc), respectively. The diameter proportion of microplastics in the range of $0.2 \sim 0.5 \text{ mm}$ was the highest. Fiber microplastics accounted for the most observed type, followed by fragments and films. Among the 24 monitoring sites, it was found that proportions of severe, moderate, and mild eutrophication and mesotrophication sites accounted for 8.33%, 58.33%, 29.17%, and 4.17% of the total sampling sites, respectively, and the main pollutant was total nitrogen (TN). Microplastics abundances in the near shore waters of Dianchi Lake were significantly positively correlated with TN concentrations ($P < 0.01$), whereas they were negatively correlated with chlorophyll a (Chl-a) concentrations, not reaching a significant level ($P > 0.05$). The microplastics abundance and TN concentrations in the north bank water near the main urban area of Kunming were significantly higher than those in the other three banks. Microplastics and TN were considered to potentially have the same origin and be attributed to the tail water discharge from WWTPs.

Key words: microplastics; Dianchi Lake; eutrophication; pollution characteristics; the near shore waters

自 20 世纪 70 年代以来, 塑料污染问题受到广泛关注, 大块塑料使用后未及时回收处置, 经风化和机械磨损作用后可形成小的塑料颗粒——微塑料^[1-3]。Thompson^[4]于 2004 年率先报道了“微塑料”一词, 目前大部分研究中把微塑料定义为粒径小于 5 mm 的塑料颗粒或碎片, 其结构性质稳定, 可在环境中存留百年之久。微塑料污染目前已成为全

球重点关注的环境问题^[5], 国内外对海洋及陆地淡水环境中微塑料丰度和污染特征开展了大量研究,

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同时还开展了海洋生物吞食微塑料、微塑料与有机污染物等有害物质的复合污染及生物毒理效应方面的研究^[6~9]. 当前国内学者不仅研究了渤海^[10]、黄海^[11]和南海^[12]等海洋环境中微塑料的污染特征, 还研究了太湖^[13]、鄱阳湖^[14]、洞庭湖^[15]、洪湖^[16]、白洋淀^[17]、青海湖^[18]、三峡库区^[19]、香溪湾^[20]和丹江口水库^[21]等内陆淡水及沉积物中微塑料污染, 而滇池等云南地区的高原淡水湖泊的微塑料污染研究鲜见报道.

滇池为云南省面积最大的高原淡水湖, 受流域内生产生活排放氮磷等因素的影响, 水质自 20 世纪 80 年代恶化, 常年呈中度或重度富营养化状态, 为国家重点治理的“三湖”之一^[22]. 目前针对滇池水体富营养化开展大量研究, 为滇池水环境保护提供有力支撑^[23], 而滇池水体中微塑料污染状况尚不明晰. 此外, Li 等^[2]对洞庭湖等长江中下游的 18 个湖泊的研究发现, 沉积物中微塑料丰度与湖水总氮 (TN) 质量浓度显著正相关. Canniff 等^[24]的研究认为微塑料能促进藻类的生长, 也有研究认为其抑制藻类生长, 导致水中叶绿素质量浓度降低^[25~27]. 滇池水体中的微塑料污染与富营养化指标间的关系尚不清楚, 本研究通过调查测定滇池近岸水体的微塑料污染及富营养化水质指标, 阐明滇池水体的微塑料污染特征, 分析滇池微塑料与氮等污染物是否同源, 探讨微塑料对藻类生长的影响. 研究结果可进一步丰富我国淡水环境微塑料污染数据, 以期为滇池等高原湖泊的微塑料污染管控提供参考, 同时也为后续进一步开展微塑料对藻类生长影响研究提供基础数据.

1 材料与方法

1.1 研究区概况

滇池属长江上游金沙江水系, 海拔约 1 885 m, 南北长约 40 km, 东西宽约 7 km, 水域面积 309.5 km², 海埂大坝将滇池分为草海和外海两部分, 北侧草海占滇池总面积的 3.6%^[28]. 滇池北岸紧邻昆明主城区, 常住人口 511.52 万 (截至 2019 年); 东岸毗邻昆明呈贡新城区, 近年来社会经济发展迅速; 南岸为大规模塑料大棚花卉和蔬菜种植区, 是滇池沿岸农业种植面积最大的区域; 西岸邻西山, 汇水面积小, 地势陡峭, 人类活动强度较北岸、东岸和南岸低.

滇池为典型的高原湖泊, 入湖河流数量多、出湖河流少, 易堆积营养物质, 具有明显的封闭-半封闭特征^[28], 且受人类生产生活干扰, 滇池面临较大的水环境压力. 滇池草海和外海水质以重度污染为主,

水质分别为 V 类和劣 V 类. 经长期治理, 滇池近 5 年的水质状况有所改善, 目前滇池草海和外海水质分别提升至 IV 类和 V 类.

1.2 样品采集和水质参数测定

在滇池近岸水体布设 24 个采样点, 如图 1 所示, 其中北岸样点编号为 1~11, 东岸为 12~17, 南岸为 18~20, 西岸为 21~24. 结合滇池狭长形的地形特征, 同时考虑到北岸入滇河流数量多, 约占入滇河流总数的一半, 北岸样点数多于其他岸. 于 2020 年 7~8 月根据 GPS 定位采集微塑料样品及水样. 参照文献^[14]的方法现场收集各样点水体的微塑料样品, 利用有机玻璃水质采样器采集 20 L 表层水 (水面下 30 cm 处), 用真空抽滤瓶及布氏漏斗抽滤, 过孔径 20 μm 的不锈钢滤网, 用纯净水将漏斗内壁物质冲洗至滤网后, 将滤网装入玻璃培养皿 ($\phi 120$ mm) 密封带回实验室. 分别用塞氏盘和哈纳 HI 98194 便携式多参数水质分析仪原位测定各样点水体的透明度 (SD)、温度 (T)、溶解氧 (DO)、pH 和氧化还原电位 (ORP). 另外采集 2 瓶 500 mL 水样低温保存运回实验室, 及时测定水样的总氮 (TN)、总磷 (TP)、叶绿素 a (Chl-a) 和高锰酸盐指数的质量浓度.

1.3 微塑料样品预处理及分析

微塑料样品预处理参考美国国家海洋与大气管

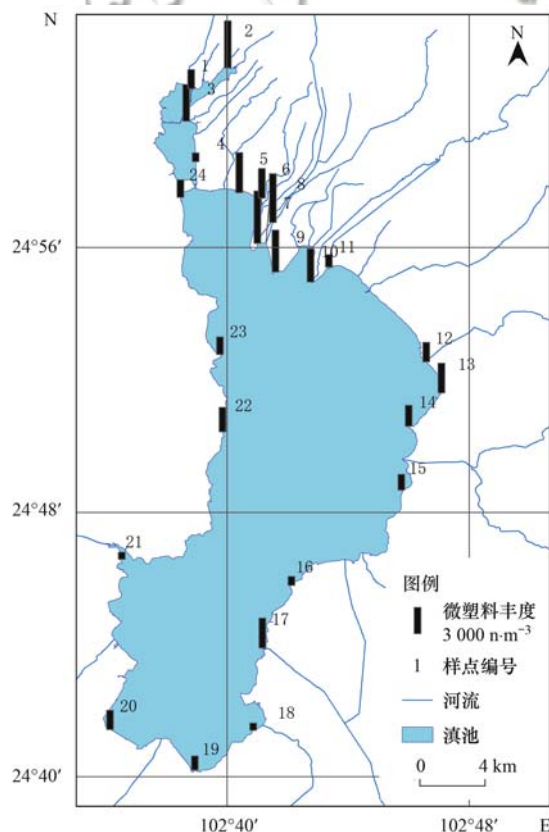


图 1 滇池近岸水体采样点分布及微塑料丰度

Fig. 1 Distribution of sampling sites and abundance of microplastics in the near shore waters of Dianchi Lake

理局(NOAA)发布的样品处理办法进行^[29].用纯净水充分冲洗滤网及培养皿内壁转入烧杯中,置于85℃的烘箱至水分蒸发,依次加入0.05 mol·L⁻¹的Fe(II)溶液和30% H₂O₂溶液各20 mL,75℃水浴加热消解至无肉眼可见有机质,按照每20 mL样品加入6 g NaCl,75℃加热溶解后,转移至装有橡胶管和止水夹的漏斗中,悬挂静置浮选24 h.弃去下层沉淀物后将剩余悬浮液过滤至0.45 μm的玻璃纤维滤膜(Whatman GF/F, φ 47 mm)上,晾干后装入玻璃培养皿中待测.借助体视显微镜(Leica M165C,德国)对微塑料样品进行镜检,观察并记录样品的颜色和形态等特征,使用Nano measure 1.2软件完成粒径测量及计数.在体视显微镜下选取30个不同粒径大小、颜色和形态的疑似微塑料样品,使用显微傅里叶红外光谱(μ-FTIR, Thermo Scientific Nicolet 10, 美国)鉴定聚合物成分.为避免二次污染,实验器材选用玻璃制品,冲洗数次后再进行实验操作,实验服装及手套等选用棉质品.

1.4 水质分析及富营养化评价方法

水样的TN、TP、Chl-a和高锰酸盐指数测定分别采用《碱性过硫酸钾紫外分光光度法》(HJ 636-2012)、《钼酸铵分光光度法》(GB 11893-89)、《水质叶绿素a的测定分光光度法》(HJ 897-2017)和《高锰酸盐指数测定》(GB 11892-89)完成.

采用综合营养状态指数(TLI)评价滇池近岸水体的营养状况,计算方法见公式(1)^[30]:

$$TLI = \sum_{j=1}^m W_j TLI(j) \quad (1)$$

式中,TLI为综合营养状态指数;TLI(*j*)为第*j*种指标的营养状态指数;W_{*j*}为第*j*种参数的相关权重;*m*为参与评价的指标个数.

营养状态指数的相关权重W_{*j*}的计算以Chl-a为基准参数,第*j*种参数归一化的相关权重计算方法见公式(2):

$$W_j = \frac{r_{ij}^2}{\sum_{j=1}^m r_{ij}^2} \quad (2)$$

式中,*r_{ij}*表示第*j*种参数与基准参数Chl-a间的相关系数;*m*为参与评价的指标个数.Chl-a与其他参数间的相关系数参考文献[31]的报道值.根据计算得到的综合富营养指数对水体的营养状态进行分级,标准如表1所示.

1.5 数据处理

以每立方米水中包含的微塑料颗粒个数表示微塑料丰度,记作“n·m⁻³”.用Microsoft Excel 2010进行数据预处理,数据相关性分析使用SPSS 23.0完

成,采用最小显著差异(LSD)进行数据差异性分析(*P* < 0.05),用Origin 9.1绘图.

表1 综合富营养指数评价标准

项目	营养状态
TLI ≤ 30	贫营养
30 < TLI ≤ 50	中营养
50 < TLI ≤ 60	轻度富营养
60 < TLI ≤ 70	中度富营养
TLI > 70	重度富营养

2 结果与分析

2.1 近岸水体微塑料丰度及成分

滇池近岸水体24个样点均有微塑料检出,丰度在800~6 000 n·m⁻³之间,平均丰度为2 867 n·m⁻³(图1).滇池微塑料丰度最高为7号样点,达6 000 n·m⁻³,最低为18和21号,均为800 n·m⁻³.微塑料丰度超过4 000 n·m⁻³的样点共有6个(2、3、5、7、8和9号),全部集中在北岸,占样点总数的25%.滇池东、南、西、北近岸水体的微塑料平均丰度分别为2 367、1 533、1 900和3 855 n·m⁻³,差异性分析结果显示北岸水体微塑料丰度显著高于其他岸(*P* < 0.05).

对选取的30个疑似微塑料颗粒进行显微傅里叶红外光谱分析(图2),共检出聚对苯二甲酸乙二醇酯(polyethylene terephthalate, PET)、聚醚型聚氨酯(polyetherurethane, PEU)、聚丙烯(polypropylene, PP)、聚乙烯(polyethylene, PE)、聚醋酸乙烯酯(polyvinyl acetate, PVAc)、聚丙烯腈(polyacrylonitrile, PAN)、聚丙烯-乙烯共聚物(polypropylene-polyethylene, PP-PE)和玻璃纸(cellophane)这8种聚合物.其中,PET、PEU、PP、PE和PVAc这5种聚合物检出比例分别为33.33%、20.00%、13.33%、10.00%和10.00%,累加超过86.66%,而PAN、PP-PE和cellophane的检出率均低于10.00%,占比较低.图2所示的PET、PEU和PVAc与标准谱图的相似度在65.37%~70.29%,略低于其他文献报道的相似度^[32].可能是滇池近岸水体中的微塑料样品,尤其是含有极性官能团成分的微塑料颗粒发生老化,导致聚合物结构改变,进而降低与标准图谱的相似度^[33].

2.2 近岸水体微塑料粒径、颜色和形态特征

根据粒径大小将观察到的微塑料颗粒分成0.2~0.5、0.5~1、1~2和2~5 mm这4类[图3(a)].一半以上的样点在各粒径范围内均有微塑料检出,54.17%的样点中0.2~0.5 mm微塑料占比最大,呈现随粒径增大数量减少的规律,与罗雅丹

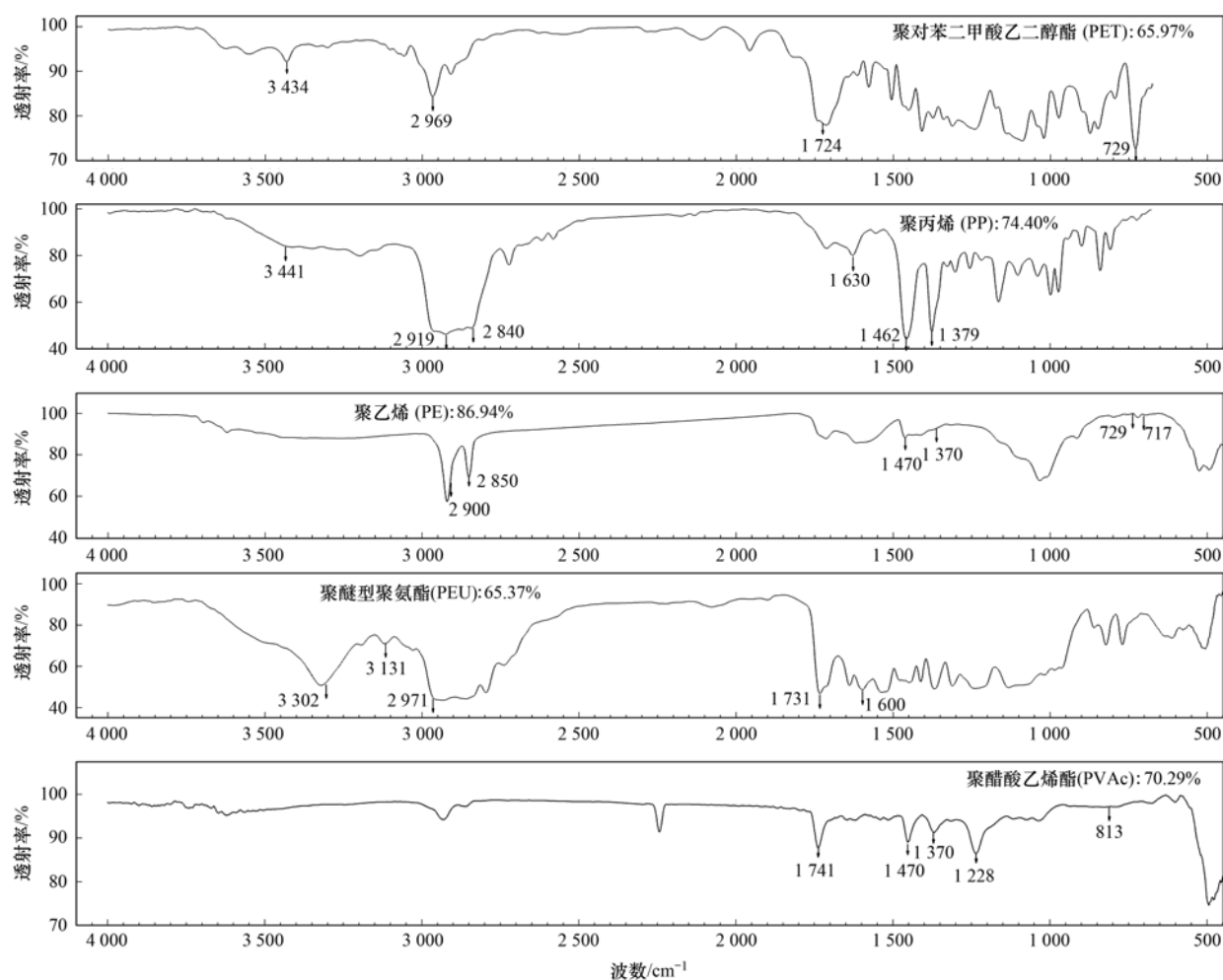


图2 近岸水体中典型微塑料显微傅里叶红外光谱图

Fig. 2 Typical micro-Fourier infrared spectroscopy of microplastics in the near shore waters

等^[34]的研究结果一致. 滇池北岸的4号和西岸的21号样点只检测到0.5~1 mm和1~2 mm的塑料颗粒,除这两个采样点外,北岸的10个样点中0.2~1 mm的微塑料颗粒数量远超1~5 mm的数量,东岸、南岸和西岸则表现为各粒径范围微塑料占比相当.

将观察到的微塑料分红色、黑色、蓝色、透明和其他这5类,滇池近岸水体微塑料颜色各异[图3(b)],北岸除3号和4号样点外均检出5种以上颜色的微塑料,高于东岸、南岸和西岸检出颜色的种类数,南岸的18号和21号样点,仅有红色和黑色微塑料检出.

将微塑料按照形貌特点分成纤维、碎片和薄膜这3类[图3(c)].各样点中纤维状微塑料比重在34.83%~100.00%之间,为滇池近岸水体大部分样点主要检出形态,其中11、16、18、21和23号样点仅有纤维状微塑料检出.滇池北岸部分样点碎片状微塑料占比较高,但数量仍少于纤维状.各样点中纤维状(图4中a)微塑料主要来源于织物、塑料编织袋和渔线.碎片状(图4中b)微塑料主要是较坚硬的塑料制品如塑料包装盒和日常生活中的塑料容器

等,经风化或在其他外力作用下破碎形成^[35,36].薄膜状(图4中c)微塑料源于一次性塑料袋和农用地膜等塑料制品的风化作用,在研究区各样点内检出比例均较低.

2.3 近岸水体富营养化状况

滇池近岸水体各样点TN、TP和高锰酸盐指数的平均质量浓度分别为4.26、0.13和7.40 mg·L⁻¹(图5),TP和高锰酸盐指数质量浓度均低于《地表水环境质量标准》(GB 3838-2002)Ⅳ类标准限值,TN质量浓度超Ⅴ类标准限值.滇池水体pH、T、DO、ORP和SD的平均值分别为7.82、19.11℃、4.26 mg·L⁻¹、75.02 mV和0.49 m.各样点间Chl-a质量浓度差异较大[图5(c)],范围在1.41~210.58 mg·m⁻³之间,22号样点最高.

参照综合营养状态指数评价标准,对滇池近岸水体的综合营养状态进行分级,结果显示处于重度、中度、轻度富营养化和中营养水平的样点分别占样点总数的8.33%、58.33%、29.17%和4.17%.滇池水体中较高的TN质量浓度为藻类繁殖提供了必要的营养条件,滇池所处的云贵高原地区全年日照时

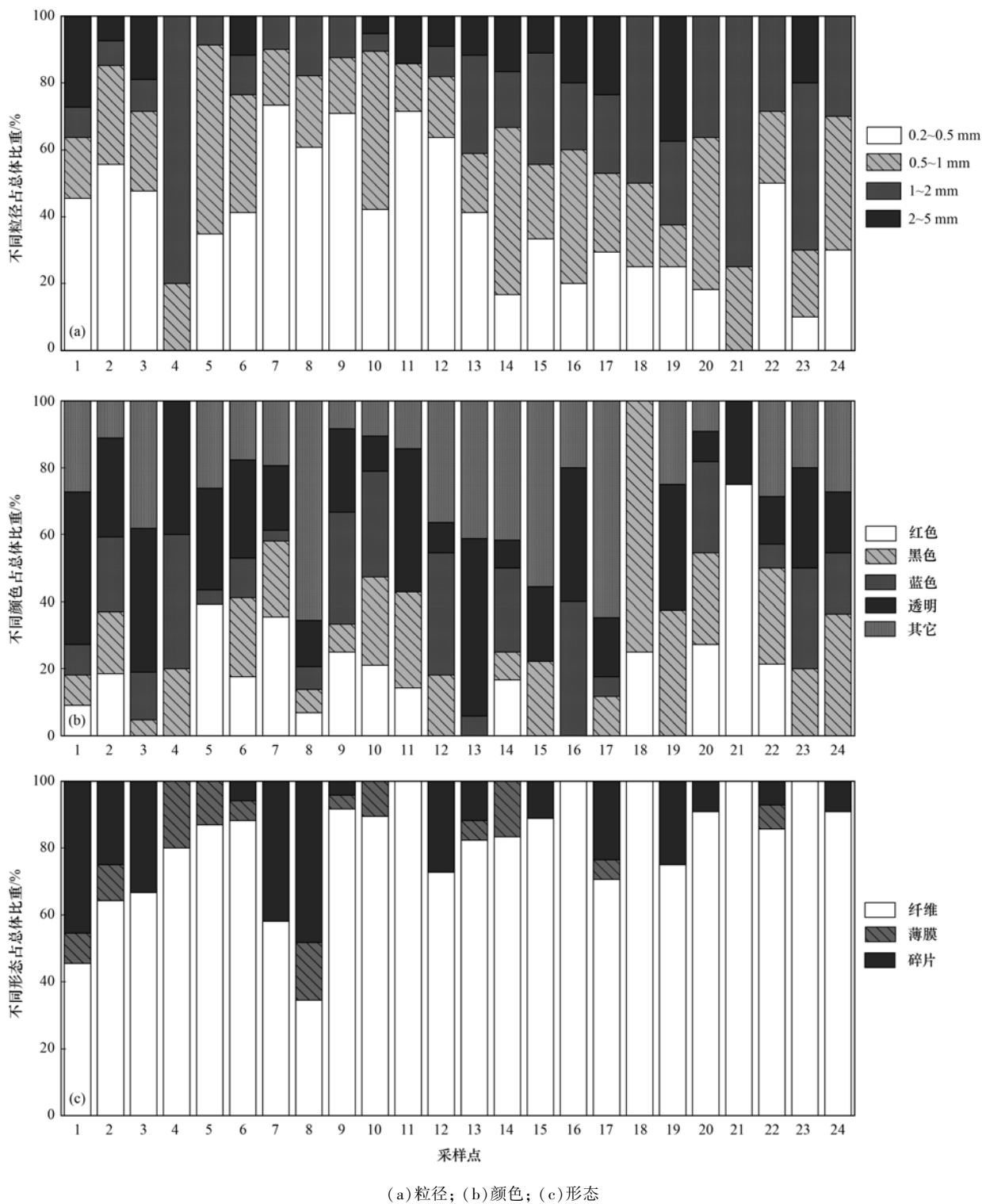


图3 滇池近岸水体各采样点微塑料的分布特征

Fig. 3 Distribution characteristics of microplastics in the near shore waters of each sampling site in Dianchi Lake

数长且气温高,采样期间平均水温较高,加速了浮游藻类繁殖,提高 Chl-a 质量浓度进而降低水体 SD^[37,38].

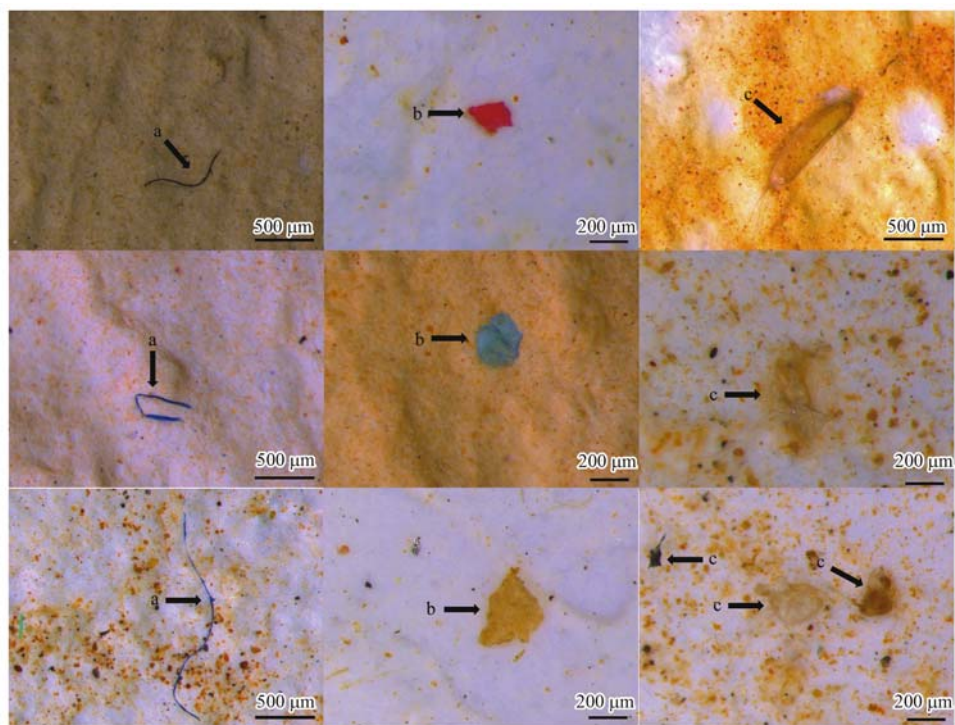
3 讨论

3.1 滇池近岸水体微塑料污染特征分析

与文献报道的其他淡水湖相比(表2),滇池近

岸水体微塑料平均丰度高于西洞庭湖、南洞庭湖^[15]和洪湖^[16],但低于周围人口密度大的太湖^[13]、鄱阳湖^[14]和长沙市城区内8个湖泊^[39].滇池近岸水体微塑料丰度低于我国水环境(淡水及海水)的平均丰度($4\,210.52\text{ n}\cdot\text{m}^{-3}$),但高于世界淡水环境的平均丰度($198.17\text{ n}\cdot\text{m}^{-3}$)^[42].

滇池近岸水体微塑料粒径分布特点与太湖^[13]和



a 表示纤维状；b 表示碎片状；c 表示薄膜状

图 4 滇池近岸水体微塑料形态

Fig. 4 Forms of microplastics in the near shore waters of Dianchi Lake

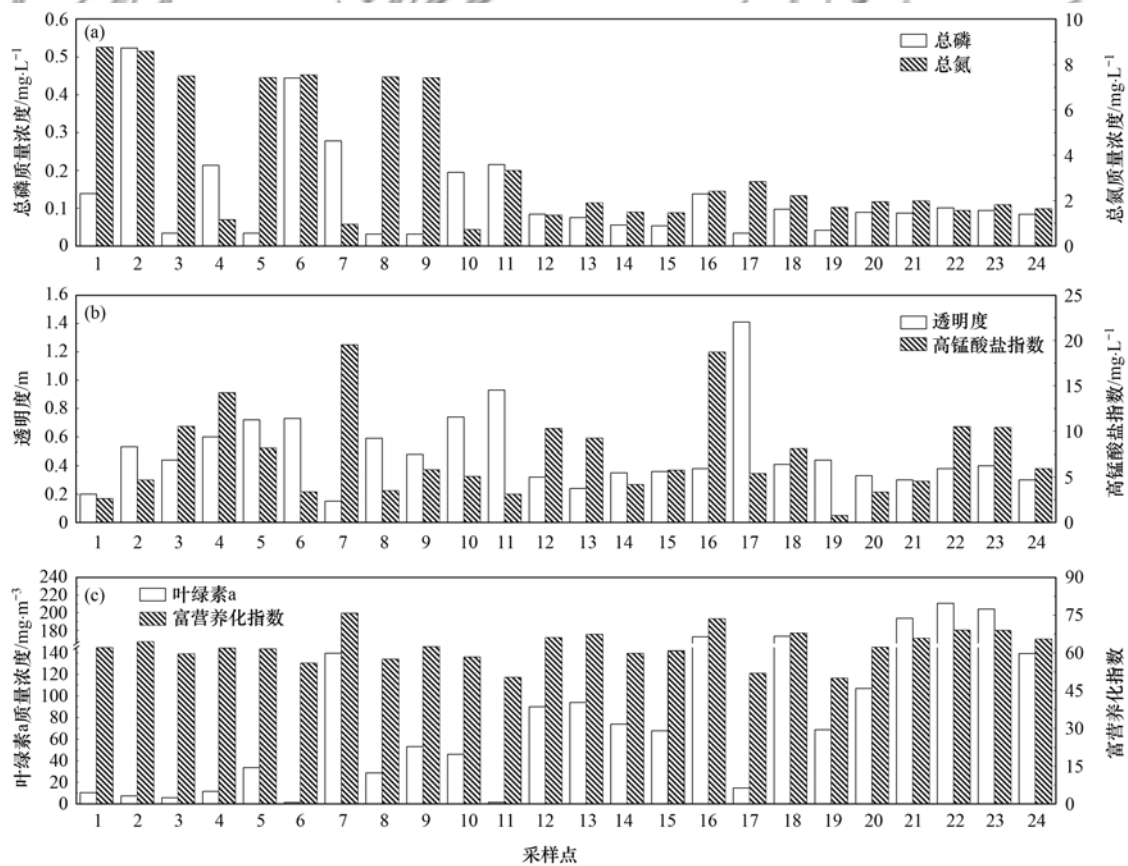


图 5 滇池近岸水体污染物质量浓度及富营养化指数

Fig. 5 Concentrations and eutrophication indices of pollutants in the near shore waters of Dianchi Lake

长沙市城区内 8 个湖泊^[39]报道的研究结果一致,小 于 1 mm 的微塑料占比最高. 现代塑料制品加工工艺

成熟,颜色种类丰富,进入环境中的塑料制品颜色差异明显,进而导致微塑料调查研究时颜色呈现多样化.现场采样调查过程中发现,部分样点有遗弃在岸边的透明渔网和渔线等,经风化和磨损等外力作用影

响下可裂解成微塑料进入滇池.此外,大气沉降过程也可增加环境中微塑料丰度^[43].随着昆明呈贡新区建设,滇池周边的农田面积不断减少,地膜和塑料大棚用量相对较少,该区域内薄膜状微塑料占比较低.

表 2 国内外部分湖泊微塑料污染特征比较

Table 2 Comparison of pollution characteristics of microplastics in lakes at home and abroad

湖泊名称	样品采集	过滤孔径 / μm	丰度 / $\text{n}\cdot\text{m}^{-3}$	主要粒径范围 / mm	主要 颜色	主要 形态	主要成分	文献
西洞庭湖	大流量采样器	45	616.67 ~ 2 216.67	<0.5	透明	纤维	PS	[15]
南洞庭湖	大流量采样器	45	716.67 ~ 2 316.67	<0.5	透明	纤维	PS	[15]
洪湖	12 V 聚四氟乙烯泵	50	1 250 ~ 4 650	<2	彩色	纤维	PP 和 PE	[16]
太湖	浮游生物网	333	3 400 ~ 25 800 ¹⁾	0.1 ~ 1	蓝色	纤维	Cellophane	[13]
鄱阳湖	钢制取水器	50	5 000 ~ 34 000 ¹⁾	0.1 ~ 0.5	彩色	纤维	PP	[14]
长沙市城区内 8 个湖泊	取水器	45	2 425 $\pm$ 247.5 ~ 7 050 $\pm$ 1 060.66	0.05 ~ 0.5	透明	线状	PP	[39]
Vesijärvi Lake, Finland	金属勺取样	/	117 100 $\pm$ 18 400 ¹⁾ (雪)	/	/	纤维	Cellophane	[40]
Vesijärvi Lake, Finland	金属钻取	/	7 800 $\pm$ 1 200 ¹⁾ (冰)	/	/	纤维	Cellophane	[40]
Chiusi Lake, Italy	拖网采集	300	2.68 ~ 3.36	0.3 ~ 1	/	纤维	/	[41]
滇池	有机玻璃水质采样器	20	800 ~ 6 000	0.2 ~ 0.5	其他	纤维	PET	本研究

1) 为便于对比,数据进行了单位换算

3.2 滇池近岸水体富营养化指标与微塑料丰度的相关性

皮尔逊相关分析结果显示(表 3),微塑料丰度与 TN 质量浓度呈极显著正相关($P < 0.01$).滇池近岸水体微塑料丰度和 TN 质量浓度的空间分异特征一致,LSD 分析发现滇池北岸水体微塑料丰度和 TN 质量浓度显著高于东岸、南岸和西岸($P < 0.05$).滇池北岸紧邻昆明市主城区,截至 2019 年城镇常住人口为 511.52 万人,人类活动强度大.此外,还有盘龙江、运粮河和宝象河等约 15 条河流由北岸注入滇池,有机物、氮和磷等污染负荷约占全湖的 70%^[44],推测滇池水体中的微塑料和 TN 主要来源于北岸的外源输入.

为保护滇池,位于滇池北岸的昆明市主城区实施雨污分流工程,生活污水收集处理率达 92%,污水进入主城区的 10 座污水处理厂进行处理,大部分尾水随十余条入滇河流排入滇池北部水域.现有的污水处理厂主要针对有机物、氮和磷等污染物的去除,而对微塑料的去除效率较低,武汉市^[45]和南京市^[46]污水处理厂对微塑料的去除效率分别为 64.4% 和 78.57%,上海市^[47]两座大型三级污水处理厂对微塑料的去除率分别为 63.25% 和 59.84%.纤维状微塑料在污水处理厂出水中的占比远高于其他形状,与滇池近岸水体中纤维状微塑料占主导的调查结果一致,间接证实滇池水体微塑料主要源于污水处理厂尾水.

另一方面,滇池近岸水体中 TP 和高锰酸盐指数质量浓度均达到《地表水环境质量标准》(GB 3838-2002)的 IV 类水标准限值,而 TN 质量浓度超

过 V 类标准限值,表明 TN 是主要污染物.昆明市主城区约一半污水处理厂采用 A²/O 工艺,而 A²/O 工艺对 TN 平均去除率显著低于 TP^[48],2019 年污水处理厂尾水负荷占滇池 TN 和 TP 的入湖负荷的 40.20% 和 8.00%^[44].因此,污水处理厂尾水排放是滇池水体 TN 主要来源.综上,昆明市主城区污水处理厂尾水中的微塑料及 TN 随地表径流进入滇池,使得滇池近岸水体中微塑料及 TN 质量浓度呈极显著正相关关系($P < 0.01$),均源自污水处理厂尾水排放,具有同源性,建议今后深入开展污水处理厂高效去除微塑料和 TN 的技术研究,优化现有污水处理工艺.

滇池近岸水体微塑料丰度与其他富营养化指标的相关性未达到显著水平,这一研究结果与 Li 等^[2]在不同营养状态湖泊的研究结果一致.其中,微塑料丰度与 Chl-a 质量浓度呈负相关关系,但未达到显著水平($P > 0.05$),表明滇池水体中的微塑料可能对藻类生长有一定抑制作用,但不明显.Wu 等^[25]研究了 PP 和 PVC 对水华微囊藻和蛋白核小球藻的影响,微塑料对微藻细胞 Chl-a 均存在极显著抑制作用,但能通过自身调节恢复正常,在高浓度的微塑料胁迫下,微藻细胞内的丙二醛(MDA)、过氧化氢酶(CAT)和活性氧(ROS)水平均极显著升高,表明微藻细胞受到氧化损伤,而低浓度微塑料对微藻的生长无明显影响.滇池等自然水体中微塑料丰度低于模拟实验中设置的微塑料浓度,其对藻类生长的抑制作用较小.此外,本研究未深入调查 0.2 mm 以下的微塑料污染特征,但更小粒径微塑料对微藻生长的影响更大^[49],今后应进一步深入开展滇池水体中

表 3 滇池近岸水体微塑料丰度与富营养化指标相关性¹⁾

Table 3 Correlations between microplastics abundances and eutrophication indices in the near shore waters of Dianchi Lake							
	丰度	SD	TP	高锰酸盐指数	TN	Chl-a	TLI
丰度	1						
SD	0.120	1					
TP	0.224	0.073	1				
高锰酸盐指数	0.053	-0.268	0.056	1			
TN	0.517 **	0.157	0.244	-0.308	1		
Chl-a	-0.368	-0.513 *	-0.246	0.402	-0.576 *	1	
TLI	0.024	-0.665 **	0.078	0.741 **	-0.237	0.707 **	1

1) **和*分别表示在0.01和0.05级别(双尾)显著相关

不同聚合物种类和更小粒径的微塑料对藻类生长的影响研究。

4 结论

(1)滇池近岸水体微塑料丰度在 800 ~ 6 000 n·m⁻³之间,平均丰度为2 867 n·m⁻³,检出的聚合物成分包括 PET、PEU、PP、PE 和 PVAc 等 8 种,粒径多集中在 0.2 ~ 0.5 mm 之间,且随粒径增加,检出数量逐渐降低。形态以纤维状为主,碎片和薄膜数量较少。

(2)滇池近岸水体处于重度、中度、轻度富营养化和中营养水平分别占样点总数的 8.33%、58.33%、29.17% 和 4.17%,主要污染物为 TN。

(3)滇池北岸的微塑料丰度与 TN 质量浓度均显著高于东岸、南岸和西岸($P < 0.05$),且二者呈极显著正相关关系($P < 0.01$),主要来源于城市污水处理厂尾水。

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