

目次

气候变化对中国夏季臭氧影响	胡安琪, 谢晓栋, 龚康佳, 侯宇晖, 胡建林 (1801)
基于 EOF 分解和 KZ 滤波的 2019~2021 年中国臭氧时空变化及驱动因素分析	王浩琪, 张裕芬, 罗忠伟, 王艳阳, 戴启立, 毕晓辉, 吴建会, 冯银厂 (1811)
华北工业城市夏季大气臭氧生成机制及减排策略	郑镇森, 窦建平, 张国涛, 李丽明, 徐勃, 杨文, 白志鹏 (1821)
2015~2020 年中国城市 PM _{2.5} -O ₃ 复合污染时空演变特征	牛笑笑, 钟艳梅, 杨璐, 易嘉慧, 慕航, 吴倩, 洪松, 何超 (1830)
2015~2021 年京津冀及周边地区 PM _{2.5} 和臭氧复合污染时空特征分析	宋小涵, 燕丽, 刘伟, 贺晋瑜, 王亚晨, 黄同林, 李园园, 陈敏, 孟静静, 侯战方 (1841)
2000~2020 年中国典型经济区 PM _{2.5} 时空变化及其与植被景观格局的关系	徐勇, 李欣怡, 黄雯婷, 郭振东, 盘钰春, 郑志威, 戴强玉 (1852)
北京市核心区冬春季大气离子沉降量特征及来源解析	赵宇, 李贝贝, 黄玉虎, 梁静, 杨洪玲, 秦建平, 朱玲 (1865)
南京近郊农田大气颗粒物及金属干沉降输入特征	刘翠英, 靳浩, 樊建凌 (1873)
西安冬季 PM _{2.5} 中不同极性水溶性有机物的污染特征及氧化潜势	罗玉, 黄沙沙, 张甜, 孙健, 沈振兴 (1882)
机动车源和民用燃料源颗粒物中有机碳和元素碳的排放特征	王红磊, 刘思略, 孙杰娟, 刘煥武, 赵天良, 裴宇僊, 可玥, 武自豪, 刘诗云 (1890)
伊犁河谷核心区春季 PM _{2.5} 组分特征及来源解析	谷超, 徐涛, 马超, 伊布提哈尔·加帕尔, 郭丽瑶, 李新琪, 杨文 (1899)
基于高分辨率网格的郑州市城镇居民 PM _{2.5} 暴露浓度与健康风险变化评估	李媛, 徐艺斐, 袁明浩, 苏方成, 王申博, 王克, 张瑞芹 (1911)
基于多源数据融合的河南省建材行业排放清单	刘晓, 胡京南, 王红梅, 杨丽, 张皓 (1924)
开封市城区冬季大气挥发性有机物污染特征及来源解析	施雨其, 郑凯允, 丁玮婷, 刘金平, 陈洪光, 高光, 王玲玲, 王楠, 马双良, 郑瑶, 谢绍东 (1933)
2020 年和 2021 年南京城区臭氧生成敏感性和 VOCs 来源变化分析	陆晓波, 王鸣, 丁峰, 喻义勇, 张哲海, 胡崑 (1943)
北京市城区夏季大气 VOCs 变化特征及臭氧生成潜势	张蕊, 孙雪松, 王裕, 王飞, 罗志云 (1954)
青岛市臭氧污染与非污染期间 VOCs 化学特征及来源解析	贾智海, 顾瑶, 孔翠丽, 宋江邦, 孟赫, 石来元, 吴建会, 刘保双 (1962)
基于总过氧自由基观测研究合肥市西郊夏季 O ₃ 生成特征	俞辉, 韦娜娜, 徐学哲, 刘芊芊, 姚易辰, 赵卫雄, 张为俊 (1974)
“大气十条”政策的节能降碳效果评估与创新中介效应	李少林, 王齐齐 (1985)
北京市减污降碳协同控制情景模拟和效应评估	俞珊, 张双, 张增杰, 翟艳芝, 刘桐坤 (1998)
基于不同排放清单的长三角人为 CO ₂ 排放模拟	马心怡, 黄文晶, 胡凝, 肖薇, 胡诚, 张弥, 曹畅, 赵佳玉 (2009)
武汉汉江水源水质变化趋势及风险分析	卓海华, 姜保峰, 徐杰, 陈洁, 陈杰, 兰秀薇, 范文重, 欧阳雪姣, 兰静 (2022)
长江武汉段水源地典型抗生素及抗性基因污染特征与生态风险评价	李柏林, 张贺, 王俊, 沙雪妮, 陈晓飞, 卓海华 (2032)
陕北矿区典型河流多环芳烃的赋存特征、来源及毒性风险分析	吴喜军, 董颖, 赵健, 刘静, 张亚宁 (2040)
典型湖泊有机聚集体时空特征及驱动因子	谢贵娟, 龚伊, 朱富成, 刘昌利, 卢宝伟, 邓辉, 汤祥明 (2052)
桂林市不同功能型公园水体微塑料的分布特征及风险评估	李沛钊, 吴莉, 黄菲菲, 林才霞, 舒小华, 张倩 (2062)
长江流域浮游植物群落的环境驱动及生态评价	张静, 胡愈圻, 胡圣, 黄杰 (2072)
环境异质性对三峡库区支流香溪河附石硅藻群落的影响及驱动作用	纪璐璐, 赵璐, 欧阳添, 杨宋琪, 郑保海, 杜雨欣, 李玉鑫, 李佳欣, 施军琼, 吴忠兴 (2083)
武汉市 3 种类型湖泊浮游植物群落特点及关键影响因素	张浩坤, 闵奋力, 崔慧荣, 彭雪, 张心怡, 张淑烟, 李竹栖, 葛芳杰, 张璐, 吴振斌, 刘碧云 (2093)
重金属污染对不同生境中微生物群落结构的影响	何一凡, 肖新宗, 王佳文 (2103)
亳清河水体细菌群落的结构和分布特征	王森, 陈建文, 张红, 李君剑 (2113)
微塑料暴露对小棒指软珊瑚 (<i>Sinularia microclavata</i>) 共生细菌群落结构和功能的影响	刘敏, 车文学, 曾映旭, 边伟杰, 吕淑果, 穆军 (2122)
上海市从源头到龙头的饮用水新型污染物分布特征及健康风险评价	严棋 (2136)
铝改性生物炭对水体低浓度氟的吸附特性	刘艳芳, 高玮, 刘蕊, 尹思婕, 张妙雨, 刘晓帅, 李再兴 (2147)
典型雌激素在微塑料上的吸附特征及位点能量分布	刘姜艳, 郑密密, 胡嘉梧, 柳玉荣, 贺德春, 潘杰 (2158)
面向工业园区废水臭氧氧化深度处理性能评价的模型污染物选择与评估	辛勃, 单超, 吕路 (2168)
基于地理探测器和多源数据的耕地土壤重金属来源驱动因子及其交互作用识别	张宏泽, 崔文刚, 刘绥华, 崔瀚文, 黄月美 (2177)
基于 APCS-MLR 和 PMF 模型的煤矸山周边耕地土壤重金属污染特征及源解析	马杰, 沈智杰, 张萍萍, 刘萍, 刘今朝, 孙静, 王玲灵 (2192)
基于蒙特卡罗模拟的铅锌冶炼厂周边农田土壤重金属健康风险评估	黄剑波, 姜登登, 温冰, 王磊, 石佳奇, 周艳 (2204)
基于 BP 神经网络预测北京市加油站周边土壤多环芳烃含量	马赛炎, 魏海英, 马瑾, 刘奇缘, 吴颐杭, 屈雅静, 田雨欣, 赵文浩 (2215)
石家庄市土壤中喹诺酮类抗生素时空分布及其风险评估	赵鑫宇, 陈慧, 赵波, 宋圆梦, 卢梦淇, 崔建升, 张璐璐, 李双江 (2223)
典型黑色岩系地质高背景区土壤和农产品重金属富集特征与污染风险	邓帅, 段佳辉, 宁墨兔, 谭林, 蒲刚, 陈际行, 齐小兵, 蒋尚智, 谢桃园, 刘意章 (2234)
岩溶区不同母质土壤 Cd 地球化学特征及玉米籽实 Cd 含量预测	戴亮亮, 徐宏根, 巩浩, 彭志刚, 肖凯琦, 吴欢欢, 许青阳, 郭军, 汤媛媛, 张俊 (2243)
龙岩市不同利用类型土壤及农作物 Pb、Cd 和 As 污染风险与贡献分析	王蕊, 陈楠, 张二喜 (2252)
小麦籽粒镉含量影响因素 Meta 分析和决策树分析	刘娜, 张少斌, 郭欣宇, 宁瑞艳 (2265)
黄土高原次生林演替过程土壤有机碳库及其化学组成响应特征	刘涵宇, 刘颖异, 张琦, 封伦, 高起乾, 任成杰, 韩新辉 (2275)
短期氮磷添加对祁连山亚高山草地土壤呼吸组分的影响	江原, 甘小玲, 曹丰丰, 赵传燕, 李伟斌 (2283)
黄河源区斑块退化高寒草甸土壤微生物多样性对长期封育的响应	杨鹏年, 李希来, 李成一, 段成伟 (2293)
不同海拔箭筈锦鸡儿根际和非根际土壤细菌群落多样性及 PICRUSt 功能预测	李媛媛, 徐婷婷, 艾喆, 魏庐璐, 马飞 (2304)
模拟酸雨及氮沉降对马尾松林土壤细菌群落结构及其多样性的影响	王楠, 钱少郁, 潘小承, 陈一磊, 白尚斌, 徐飞 (2315)
磷石膏和碱蓬对盐渍化土壤水盐及细菌群落结构的影响	刘月, 杨树青, 张万峰, 姜帅 (2325)
菌渣与化肥肥施对稻田土壤微生物群落组成及多样性的影响	耿和田, 王旭东, 石思博, 叶正钱, 周文晶 (2338)
增氧对不同秸秆还田稻田田面水养分动态及温室气体排放的影响	胡锦涛, 薛利红, 钱聪, 魏利祥, 曹帅 (2348)
外源褪黑素对胁迫下水稻幼苗生长和抗氧化系统的影响	储玉檀, 李颜, 黄益宗, 保琼莉, 孙红羽, 黄永春 (2356)
面向 2035 的节能与新能源汽车全生命周期碳排放预测评价	付佩, 兰利波, 陈颖, 郝卓, 邢云翔, 蔡旭, 张春梅, 陈轶嵩 (2365)
农田土壤微塑料分布、来源和行为特征	薄录吉, 李冰, 张凯, 马荣辉, 李彦, 王艳芹, 孙斌, 刘月岩 (2375)
农田土壤除草剂污染的修复技术研究进展	胡芳雨, 安婧, 王宝玉, 徐明恺, 张惠文, 魏树和 (2384)
我国黑土地农田土壤除草剂残留特征研究及展望	李睿, 吴秋梅, 赵归梅, 胡文友, 田康, 黄标, 吴祥为, 刘峰, 赵玉国, 赵永存 (2395)
《环境科学》征订启事(1910)	《环境科学》征稿简则(1984)
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桂林市不同功能型公园水体微塑料的分布特征及风险评估

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摘要: 城市公园水体环境容量小, 自净能力差, 更容易受微塑料影响而造成水体微生态系统的失衡. 以公园的功能特点(综合型、社区型和生态型)为基础, 通过现场采样、显微观察和傅里叶红外光谱等方法, 调查了桂林市公园水体微塑料的分布特征, 并采用微塑料风险指数(H)和负荷指数(PLI)评估了微塑料的污染风险. 结果表明, 公园表层水和沉积物中微塑料的丰度范围分别为 $104.67 \sim 674.44 \text{ n} \cdot \text{m}^{-3}$ 和 $95.57 \sim 877.78 \text{ n} \cdot \text{kg}^{-1}$. 微塑料形状主要包含碎片、纤维、薄膜和颗粒, 且以小于 1 mm 的碎片和纤维为主. 微塑料聚合物有聚乙烯和聚对苯二甲酸乙二醇酯. 不同功能公园水体的微塑料丰度差异性显著, 其中综合型公园的微塑料丰度最高. 公园水体微塑料丰度与公园功能和入园人数密切相关. 公园表层水的污染风险较低, 而沉积物的污染风险相对较高. 研究表明, 旅游是桂林城市公园水体微塑料污染的重要来源, 桂林市公园水体中微塑料污染风险总体属于轻度污染, 但仍需关注其在城市小型淡水水域中的累积风险.

关键词: 微塑料; 表层水; 沉积物; 城市公园; 分布特征; 风险评估

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Distribution Characteristics and Risk Assessment of Microplastics in Water of Different Functional Parks in Guilin

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Abstract: The water environment capacity of urban parks is small, and their self-purification ability is poor. They are also more likely to be affected by microplastics (MPs), which cause an imbalance of the water micro-ecosystem. Based on the functional characteristics of parks (comprehensive park, community park, and ecological park), this study investigated the distribution characteristics of MPs in the water of Guilin parks through spot sampling, microscopic observation, and Fourier transform infrared spectroscopy. In addition, the pollution risk index and the pollution load index were used to evaluate the pollution risk of MPs. The results showed that the abundances of MPs in the park surface water and sediments ranged from $104.67 \sim 674.44 \text{ n} \cdot \text{m}^{-3}$ and $95.57 \sim 877.78 \text{ n} \cdot \text{kg}^{-1}$, respectively. There were four main shape types of MPs: fragments, fibers, films, and particles. MPs were dominated by fragments and fibers with small sizes ($< 1 \text{ mm}$). The polymers of MPs were polyethylene and polyethylene terephthalate. There were significant differences in the abundance of MPs in the water of different functional parks, and the abundance of MPs in comprehensive parks was the highest. The abundance of MPs in park water was closely related to the function of the park and the number of people entering the park. The pollution risk of MPs in the surface water of Guilin parks was low, whereas the pollution risk of MPs in sediments was relatively high. The results of this study indicated that tourism was an important source of MPs pollution in the water of Guilin City parks. The pollution risk of MPs in the water of Guilin City parks was mild. However, the pollution risk of MPs accumulated in small freshwater waters of urban parks requires continued attention.

Key words: microplastics; surface water; sediments; urban park; distribution characteristics; risk assessment

水环境中的塑料在物理风化和太阳光等外界因素的影响下会裂解成小尺寸的微塑料($< 5 \text{ mm}$)被生物摄入, 并沿着食物链转移^[1]. 底栖鱼类^[1]、贻贝^[2]、江豚^[3]和铜锈环棱螺^[4]等体内均检测到微塑料. 微塑料在生物体内的累积可能会抑制生物的发育和繁殖^[5], 同时还会引起微生物群落结构失衡^[6]. 此外, 微塑料作为载体会与水中的其它污染物(重金属^[7]、抗生素^[8]和农药^[9])发生相互作用, 影响污染物在水中的迁移转化, 间接地促进污染物的转移, 从而引起更大的生态风险. 因此, 水环境中微塑料的产生、迁移和归趋一直是人们关注的热点.

目前淡水中微塑料的研究主要集中在大型湖泊、河流、河口和城市河道的表层水及沉积物

上^[10~12]. 有研究表明, 人类活动与水体功能直接影响研究区域内微塑料的赋存情况^[13]. 城市公园水体是城市生态环境的重要组成部分, 它在净化水质、调节微气候、补充地下水、维持生物多样性和降解污染物等方面发挥着重要作用^[14,15]. 然而, 由于城市公园水域面积较小, 其环境容量和自净能力不及湖泊、河流和河口等大型水体. 城市公园水体更容易受污染物影响造成水体微生态系统的失衡, 进而失去景观水的功能, 甚至影响周围居民生活质

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1.2 样品采集

2021 年夏季采集了表层水和沉积物的样品,每个公园选择 3 个不同的采样点采集 3 份样本,采样点使用 GPS 均匀分布定位. 使用 10 L 不锈钢桶收集表层水,把收集 5 次共 50 L 的表层水依次通过 75 μm 的不锈钢筛网过滤^[21],用去离子水冲洗筛网,将截留在筛网上的残渣冲洗到准备好的容器中,密封后在 4℃ 环境下保存. 为了防止样品被污染,减小误差,每次采样前都会用去离子水反复冲洗不锈钢筛网和容器. 每个采样点用彼得森采泥器抓取 1 kg 底层沉积物,挑出杂质接着用去离子水冲洗表面残留后丢弃. 处理后样品放入铝箔采样袋中冷藏保存.

1.3 样品处理与分析

将带回实验室的表层水样品倒入烧杯中,反复润洗采样容器. 用手持式放大镜 (10×) 进行初步分选,将可以观察到的微塑料挑出置于玻璃培养皿的滤膜上. 剩余水样通过 0.45 μm 滤膜抽滤后,用去离子水冲洗转移到 1000 mL 烧杯中,加入 200 mL 30% 过氧化氢,在室温下消化 24 h,加入 800 mL 饱和氯化钠溶液 (密度为 1.2 $\text{g}\cdot\text{cm}^{-3}$),充分搅拌后静置 24 h,收集上清液后过 0.45 μm 滤膜,将截留有微塑料的滤膜置于玻璃培养皿中,等待下一步处理.

沉积物样品先剔除植物残体、碎石和贝壳等杂质,60℃ 烘干至恒重后过 25 目筛. 称取 50 g 过筛后的样品,加入饱和的氯化钠溶液 (密度为 1.2 $\text{g}\cdot\text{cm}^{-3}$) 静置 24 h 后将上清液移至另外一个烧杯中,浮选过程重复 3 次. 将 3 次浮选的上清液抽滤,收集滤膜上的残留物到离心管内,离心 10 min 后,取上清液倒入烧杯中. 然后加入 30% 的过氧化氢在 60℃ 的条件下消解 3~4 d. 消解后再次离心,取上清液,经 0.45 μm 滤膜抽滤,得到的滤膜放置于培养皿中,盖上盖子,置于 25℃ 烘箱中烘干 24 h 后待分析.

将干燥后的滤膜放于立体显微镜下 (LEICA S8APO) 观察滤膜上的微塑料,并拍照记录. 表层水中的微塑料的丰度表示为“ $\text{n}\cdot\text{m}^{-3}$ ”,沉积物中的微塑料丰度表示为“ $\text{n}\cdot\text{kg}^{-1}$ ”. 使用傅里叶变换显微红外光谱仪 (Nicolet iN 10, Thermo Fisher, USA) 对挑选出来的微塑料进行分析,确定微塑料的聚合物类型.

1.4 风险评估

实验采用微塑料风险指数 (H) 和污染物负荷指数 (PLI) 两种模型对桂林市公园微塑料污染风险进行评估^[22, 23],微塑料风险指数 (H) 计算公式如下:

$$H = \sum P_n \times S_n$$

式中, H 为聚合物的风险指数; P_n 为每个采样点每种聚合物的百分比; S_n 为各类塑料聚合物的危险评分. 聚对苯二甲酸乙二醇酯 (PET) 和聚乙烯 (PE) 的 S_n 值分别为 4 和 11^[22].

污染物负荷指数评估模型定义如下:

$$CF_i = C_i / C_{oi}$$

$$PLI = \sqrt[n]{CF_i}$$

$$PLI_{zone} = \sqrt[n]{PLI_1 \times PLI_2 \times \cdots \times PLI_n}$$

式中, CF_i 为微塑料的污染系数; C_i 为某个采样点微塑料的实测丰度; C_{oi} 为微塑料丰度参考值,目前理论上关于 C_{oi} 的选择争议较大,此次研究选择 Everaert 等^[24] 利用数学模型估算出的水体和沉积物中微塑料的安全浓度 (即对生物体无效浓度) 作为微塑料丰度参考值,其中水体和沉积物中微塑料的丰度参考值分别为 6 650 $\text{n}\cdot\text{m}^{-3}$ 和 540 $\text{n}\cdot\text{kg}^{-1}$; PLI 为某采样点的微塑料污染负荷指数; n 为采样点个数; PLI_{zone} 为研究区域微塑料污染负荷指数. 当 $PLI \leq 1$ 时,该区域属于轻度污染, $1 < PLI \leq 2$ 时为重度污染, $PLI > 2$ 时为极强污染.

1.5 数据处理

数据的处理使用软件 IBM SPSS Statistics 26.0 进行,采用 Pearson 相关分析对公园入园人数和微塑料丰度进行分析,采用单因素方差分析 (One-way ANOVA) 对不同公园的微塑料丰度进行分析,所有数据结果均在显著水平为 0.05 情况下检验. 采样点分布图用 ArcGis 10.2 绘制,其他图件用 Origin 2018 绘制.

1.6 质量控制

为避免样品受到外界微塑料的污染,在采样和实验全程要求穿戴棉质实验服及手套,避免样品接触一切塑料制品. 烧杯使用锡箔纸密封,微塑料的提取及鉴定在超净实验室进行. 为确保实验的准确性,实验室处理过程中,均设置空白对照组,即在超净实验室中放置湿润的空白滤膜,空白组未检出微塑料.

2 结果与讨论

2.1 微塑料的丰度特征

2.1.1 表层水

微塑料在所有表层水样品中的检出率为 100%. 桂林市公园表层水中的微塑料丰度为 104.67~674.44 $\text{n}\cdot\text{m}^{-3}$ [图 2(a)]. 8 个不同公园的表层水中微塑料丰度的分布上具有显著性差异 ($P < 0.05$). S3 和 S6 的表层水微塑料丰度远高于其他采样点,达到 674 $\text{n}\cdot\text{m}^{-3}$ 和 664 $\text{n}\cdot\text{m}^{-3}$. S3 是桂林市的热门旅游景点,近 3 年平均客流量达到 53 万人,

因此使用并丢弃到环境中大量的塑料制品可能导致 S3 表层水中的微塑料丰度高于其他 3 个综合型公园. S6 作为社区型公园代表, 其表层水微塑料丰度略低于 S3, 但远远高于另外两个社区型公园 S5 和 S7. 现场调研发现 S6 有生活污水直接排入, 这可能是导致 S6 微塑料丰度高的直接原因. 表层水中微塑料丰度最低的是 S8 ($104.67 \text{ n}\cdot\text{m}^{-3}$), 由于 S8 是生态型公园, 其作用主要是保持水土、涵养水源和调节气候, 娱乐性较低, 游客稀少, 微塑料因缺少输入而在该公园水体中不易积累.

与同样采用过滤法进行调研的其它水体中微塑料的丰度相比(表 2), 桂林市公园表层水微塑料丰度明显低于洞庭湖^[25]、鄱阳湖^[26]、乌梁素海^[27]和瑞士的萨索罗湖^[28], 但高于芬兰的 Kallavesi 湖^[29]和印度的恒河^[30]. 与巴基斯坦的拉瓦尔湖^[31]和俄罗斯的贝加尔湖^[32]相比其丰度相似. 但总体来说, 桂林市公园表层水微塑料丰度相对较低, 这可能是因为很多大型湖泊是污水厂或排水系统的受纳水

体, 这使其成为微塑料在内陆淡水中重要的汇集地.

2.1.2 沉积物

沉积物样品中同样全部检测出了微塑料, 沉积物中微塑料的丰度为 $95.57 \sim 877.78 \text{ n}\cdot\text{kg}^{-1}$ [图 2 (b)]. S2 和 S4 沉积物中的微塑料丰度显著高于 S1 和 S3, 这可能是因为 S2 和 S4 的公园湖泊中有大量人工种植的挺水植物. 这些挺水植物在种植时, 用来包裹根部的塑料薄膜或壳没有清除, 这些塑料制品在水中不断经受水流冲击后破碎形成微塑料并停留在沉积物中. 与表层水情况相同, S8 沉积物中微塑料丰度最低 ($95.57 \text{ n}\cdot\text{kg}^{-1}$), 远低于其他公园. 沉积物中的微塑料丰度容易受到水体扰动的影响. S3 较多的水上娱乐项目使公园不同深度的水交换频繁. S5 与河流相连, 水体流动性较大, 这些水体环境不利于微塑料的沉降. 而 S6 和 S7 是封闭水域, 水体扰动程度小, 微塑料更容易沉降. 本次研究区域内沉积物中微塑料的丰度高于大部分其他的研究的结果(表 2), 这可能也是因为公园水域面积小, 水体流动

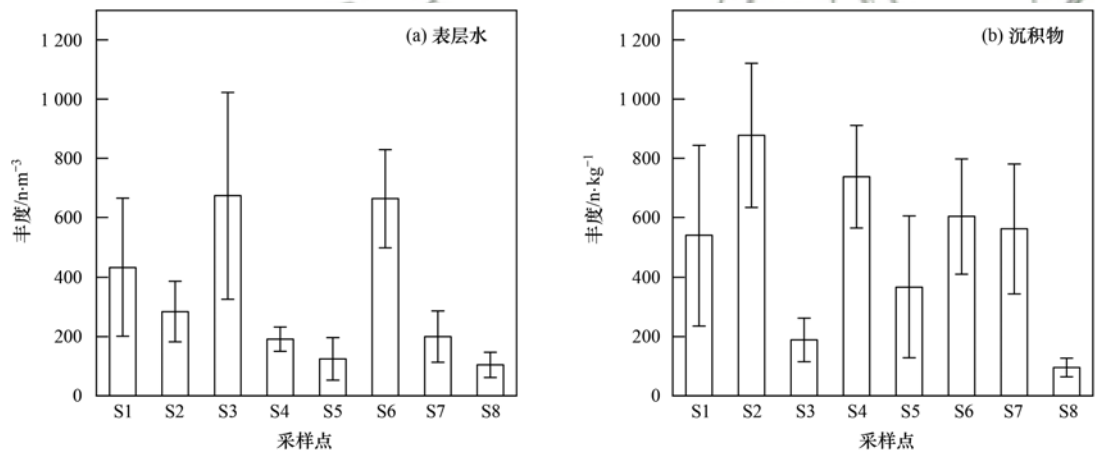


图 2 桂林市公园表层水和沉积物中的微塑料丰度

Fig. 2 Abundance of microplastics in surface water and sediments of park waters in Guilin

表 2 全球湖泊微塑料污染情况

Table 2 Microplastic pollution in global lakes

国家	研究区域	表层水中微塑料丰度 / $\text{n}\cdot\text{m}^{-3}$	沉积物中微塑料 丰度/ $\text{n}\cdot\text{kg}^{-1}$	聚合物 主要类型	主要形状	文献
中国	太湖	— ¹⁾	11.0 ~ 234.6	玻璃纸和 PE	纤维	[13]
中国	洞庭湖	366.67 ~ 2 316.67	200 ~ 1 150	PE 和 PS	纤维	[25]
中国	鄱阳湖	5 000 ~ 34 000	54 ~ 506	PP 和 PE	纤维	[26]
中国	乌梁素海	1 400 ~ 10 120	—	PE	纤维	[27]
瑞士	萨索罗湖	微塑料 2 600, 纤维 4 400	—	PE	纤维	[28]
芬兰	Kallavesi 湖	> 300 μm , 1.8 ± 2.3 ; 100 ~ 300 μm , 12 ± 17 ; 20 ~ 100 μm , 155 ± 73 ;	—	PE、PP 和 PE	纤维	[29]
印度	恒河	38 ± 4	—	人造纤维	纤维	[30]
巴基斯坦	拉瓦尔湖	—	142	PE 和 PP	纤维	[31]
俄罗斯	贝加尔湖	291 ± 252	—	PP	碎片	[32]
中国	骆马湖	—	120 ~ 1 000	PE	纤维	[34]
中国	雨山湖	—	439.9	PP 和 PE	纤维	[35]
坦桑尼亚、乌干达和肯尼亚	维多利亚湖	—	0 ~ 108	PE	碎片	[36]
英国	Edgbaston Pool 湖	—	250 ~ 300	—	纤维和薄膜	[37]

1) “—”表示参考文献无此数据

性和交换能力不及大型湖泊,从而更有利于微塑料在沉积物中的累积^[33].

2.2 微塑料的形貌与组分特征

图3给出了各采样点表层水和沉积物中典型微塑料的形貌.微塑料主要形状是碎片和纤维.表层水中碎片占54.09%、纤维占36.20%[图4

(a)],沉积物中碎片占60.61%、纤维占24.93%[图4(c)].一般来说,碎片状微塑料主要来自于大型塑料的裂解^[38],纤维状微塑料主要来源是衣物等人工合成纤维纺织品的清洗^[39].城市公园中纤维状微塑料主要来源可能为大气沉降和地表径流^[40,41].

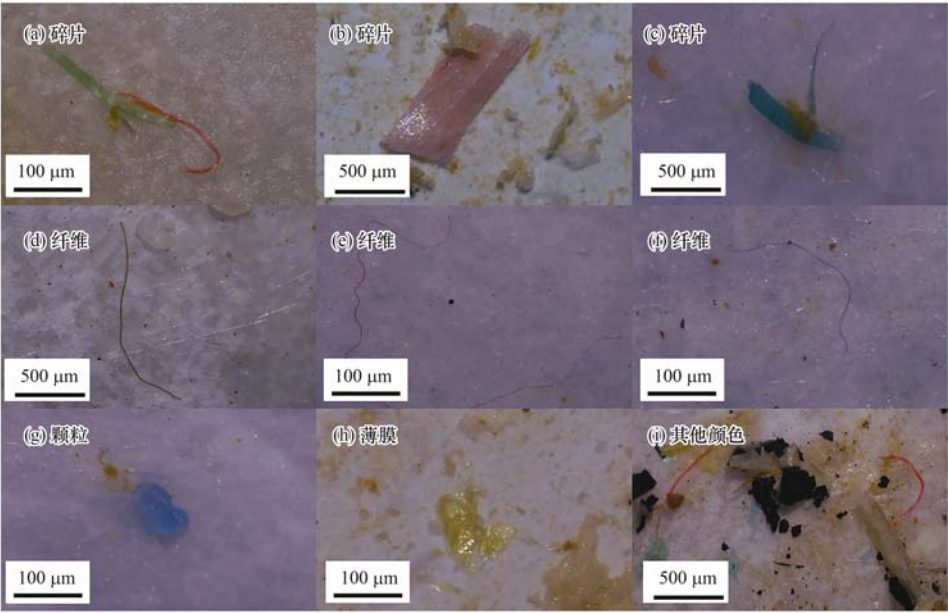


图3 桂林市公园表层水和沉积物中不同形状的微塑料

Fig. 3 Microplastic shapes in surface water and sediments of park waters in Guilin

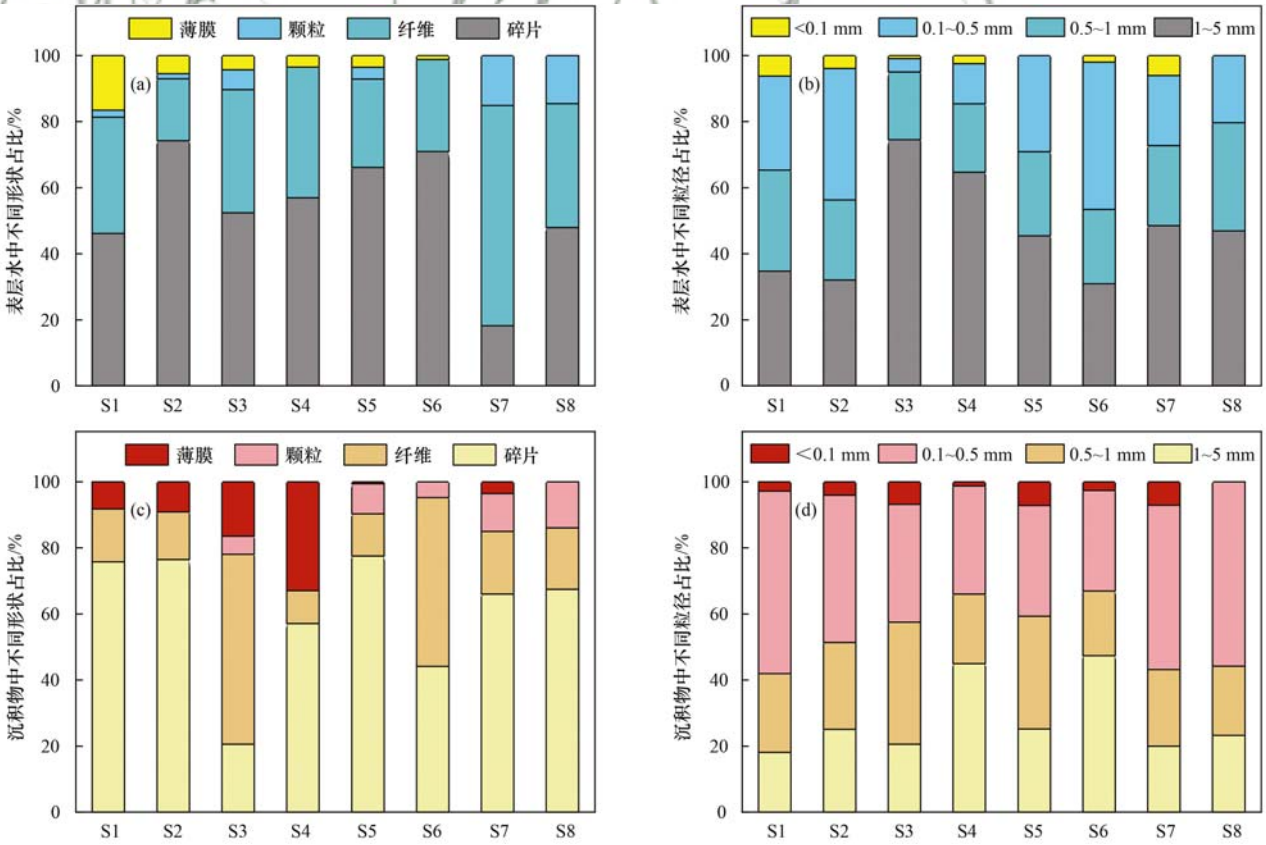


图4 桂林市公园表层水和沉积物中微塑料的形状和粒径分布

Fig. 4 Microplastic shape and size distributions in surface water and sediments of park waters in Guilin

不同粒径微塑料在不同采样点中的占比见图 4 (b) 和图 4 (d). S3 和 S4 两个公园表层水中 1 ~ 5 mm 的微塑料数量占有明显优势, 其它采样点微塑料则以 1 mm 以下粒径为主. 沉积物中的 1 mm 以下粒径的微塑料在各采样点占 60% 以上. 表层水和沉积物中微塑料粒径分布与黄河下游河口^[42]、乌梁素海^[11] 和鄱阳湖^[43] 研究结果一致. 桂林市属于亚热带季风气候, 降雨总量大, 降雨形成的地表径流容易携带微塑料等污染物进入到城市公园湖泊中, 且地表径流水的剪切力可能会加速微塑料的裂解. 小尺寸 (< 1 mm) 微塑料更易富集环境污染物, 并被生物摄食, 因此小尺寸的微塑料潜在的环境风险更大, 需要更多关注.

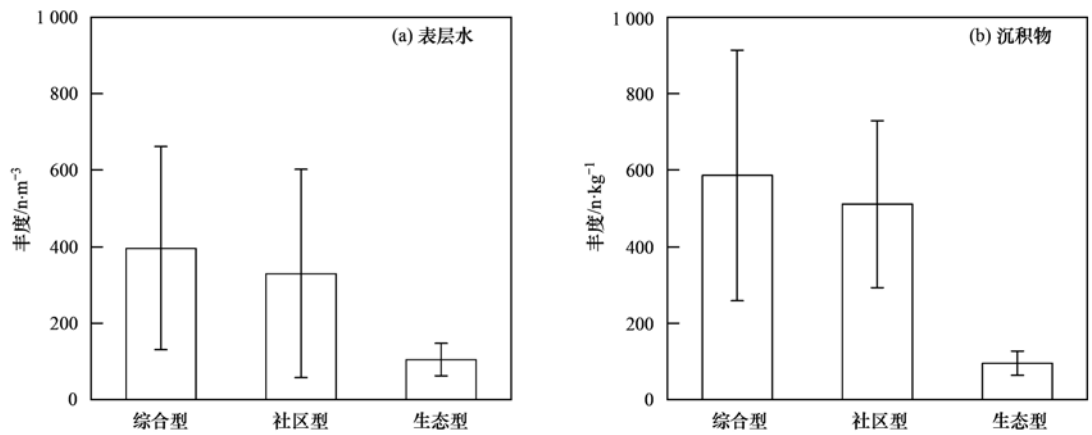


图5 桂林市不同功能型公园表层水和沉积物中微塑料丰度

Fig. 5 Abundance of microplastics in surface water and sediments of different functional park waters in Guilin

塑料的外源输入途径比综合型和社区型公园要少, 因此生态型公园的微塑料丰度低.

不同功能型公园与微塑料的形状和尺寸关系见图 6. 在桂林市公园水体中, 公园类型与微塑料尺寸之间没有显著性差异 ($P > 0.05$). 主要原因可能是所有采样点的微塑料来源没有明显不同. 相对而言, 社区型公园中颗粒状微塑料较多, 可能是因为采样点 S7 接纳的部分生活污水导致社区型公园颗粒状微塑料数量高于另外两个类型的公园. 生活污水中颗粒状微塑料主要来自个人护理产品, Gouin 等^[44] 研究显示, 3 亿人在个人护理品中使用了 261 t 的聚乙烯微塑料.

城市公园的功能特征可以影响环境中微塑料的分布. 为了说明人类活动对微塑料分布的影响, 研究进一步分析了微塑料分布与公园入园人数之间关系. 根据桂林市相关部门提供的近 3 年公园入园人数数据, 对公园微塑料丰度和入园人数进行皮尔逊相关性分析, 结果见表 3. 其中 Sig. (双尾) 值为 0.009, 小于 0.01, 表明桂林市公园微塑料与入园人数之间存在极显著的相关性. 皮尔逊相关性的值为

2.3 城市公园微塑料分布与城市公园类型和入园游客数量的关系

根据公园的功能特点, 综合型 (S1 ~ S4)、社区型 (S5 ~ S7) 和生态型 (S8) 公园的微塑料丰度情况见图 5. 各类型公园表层水中微塑料丰度范围为 104.67 ~ 395.84 $n \cdot m^{-3}$, 不同类型公园表层水的微塑料丰度大小顺序为: 综合型 > 社区型 > 生态型. 沉积物中微塑料的丰度范围为 95.57 ~ 586.11 $n \cdot kg^{-1}$, 不同类型公园的沉积物的微塑料丰度大小顺序为: 综合型 > 社区型 > 生态型. 综合型公园由于其功能的多样性, 进入公园的人群量和活动范围更广, 由此带来的塑料垃圾的输入量更大, 更容易累积微塑料. 而生态型公园主要功能是改善生态环境, 其

0.881, 则说明桂林市公园微塑料丰度与入园人数之间存在显著正相关. 这充分说明了人类活动是城市公园微塑料的主要来源. 其它研究也表明, 游客众多的海滩的微塑料丰度值会相对较高^[45]. 对青海湖^[46]、蒙古湖^[47] 和意大利的加尔达湖^[48] 的微塑料调研研究也认为旅游是微塑料污染的重要来源.

表3 桂林市公园微塑料丰度与入园人数相关性分析¹⁾

Table 3 Correlation analysis between the abundance of microplastics and the number of tourists for parks in Guilin		
项目	类型	入园人数
桂林市公园微塑料丰度	皮尔逊相关性	0.881 **
	Sig. (双尾)	0.009

1) ** 表示相关性在 0.01 水平极显著相关 (双尾)

2.4 微塑料的聚合物类型和污染风险评估

根据 FTIR 分析结果 (图 7), 桂林市城市公园微塑料聚合物类型主要为聚乙烯 (PE, 84%) 和聚对苯二甲酸乙二醇酯 (PET, 16%). 所有的样品中只有 PE 和 PET 被检出, 这与它们的广泛使用密不可分. PET 常被用于生产纺织品, 如衣服、毛毯和枕芯填充材料. PE 被广泛应用于农用薄膜、食品包装袋、塑

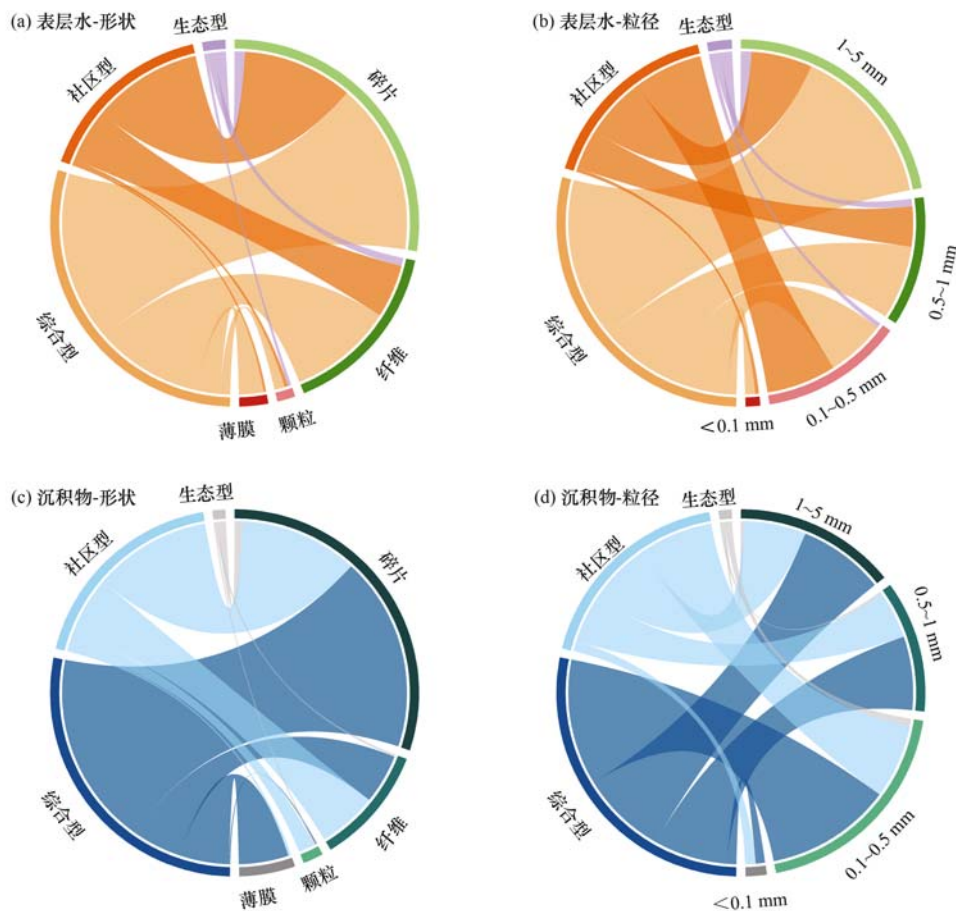


图 6 桂林市不同功能型公园表层水和沉积物中微塑料形状与粒径分布

Fig. 6 Microplastic shape and size distributions in surface water and sediments of different functional park waters in Guilin

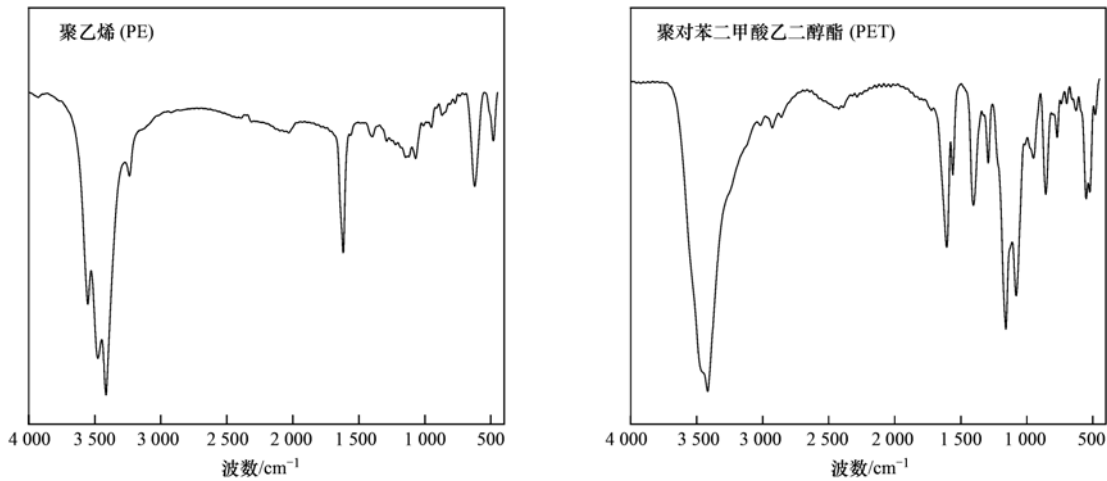


图 7 桂林市公园微塑料红外光谱图

Fig. 7 Fourier transform infrared spectroscopy of microplastics for parks water in Guilin

料瓶和最常见的塑料购物袋. PE 和 PET 目前是内陆淡水中普遍存在的微塑料类型.

根据 1.4 节中所述的风险评价方法,桂林市微塑料风险指数 (H) 为 5.12, 低于中国乌拉特前旗^[11]、东亚海到北极盆地^[49]和青海省的湟水河流域^[50]的风险指数,其风险类别等级为 I (低风险). 各采样点的污染负荷指数 PLI 值见图 8. 表层水的

PLI 范围为 0.12 ~ 0.31, 均不超过阈值 1, 属于轻度污染. 沉积物的 PLI 范围为 0.42 ~ 1.27, 其中, S2、S4、S6 和 S7 的 PLI 都超过了阈值 1, 属于重度污染, 其余均为轻度污染. 表层水和沉积物的总体 PLI_{zone} 值分别为 0.20 和 0.91, 属于轻度污染. 可见桂林市公园水体的微塑料污染风险总体评估为低风险. 但需要指出的是, 虽然桂林市的微塑料污染风险

和污染负荷指数总体评估都为低风险,但该风险评估仅仅考虑了微塑料本身的毒性及其在环境中的丰度.作为污染物载体的微塑料与其它有毒有害污染物的相互作用可能引起复杂的风险效应.同时,个别

采样点的沉积物中微塑料污染处于重度污染,可能对底栖水生生物构成直接威胁.桂林市作为重要的世界级旅游城市,应该重视微塑料对生态环境的影响,规范塑料制品的使用,加强对塑料垃圾的回收.

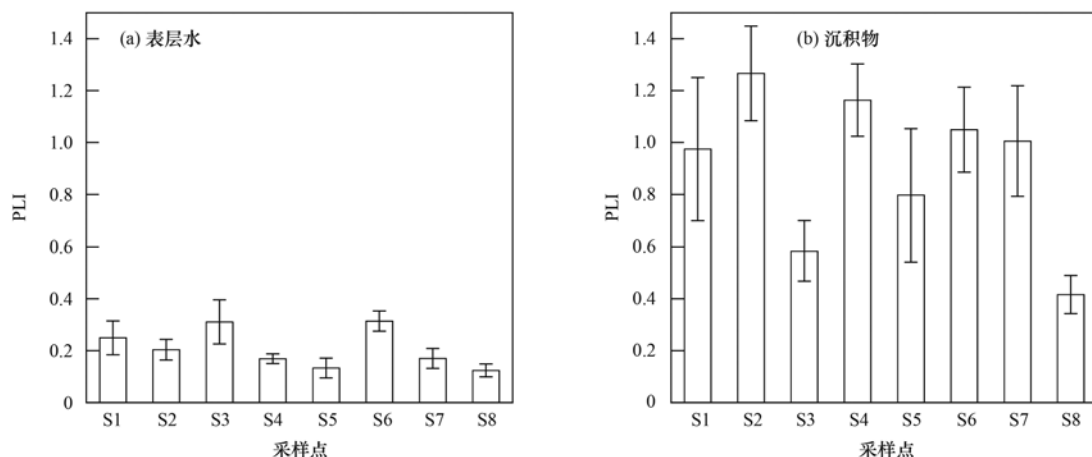


图8 桂林市公园微塑料各采样点 PLI 值

Fig. 8 PLI value of microplastics in each sampling point of Guilin Parks

3 结论

(1) 桂林市公园表层水和沉积物中微塑料的检出率 100%. 桂林市公园表层水和沉积物中的微塑料以碎片和纤维为主,小尺寸(<1 mm)的微塑料占据了主要部分,检出微塑料聚合物主要是聚乙烯和聚对苯二甲酸乙二醇酯.

(2) 不同类型公园的微塑料丰度差异性显著. 研究区域内的微塑料丰度与公园的功能和入园人数密切相关,旅游是桂林城市公园微塑料污染的重要来源.

(3) 微塑料风险指数(H)和污染物负荷指数(PLI)评估结果表明桂林市公园微塑料污染风险较低.

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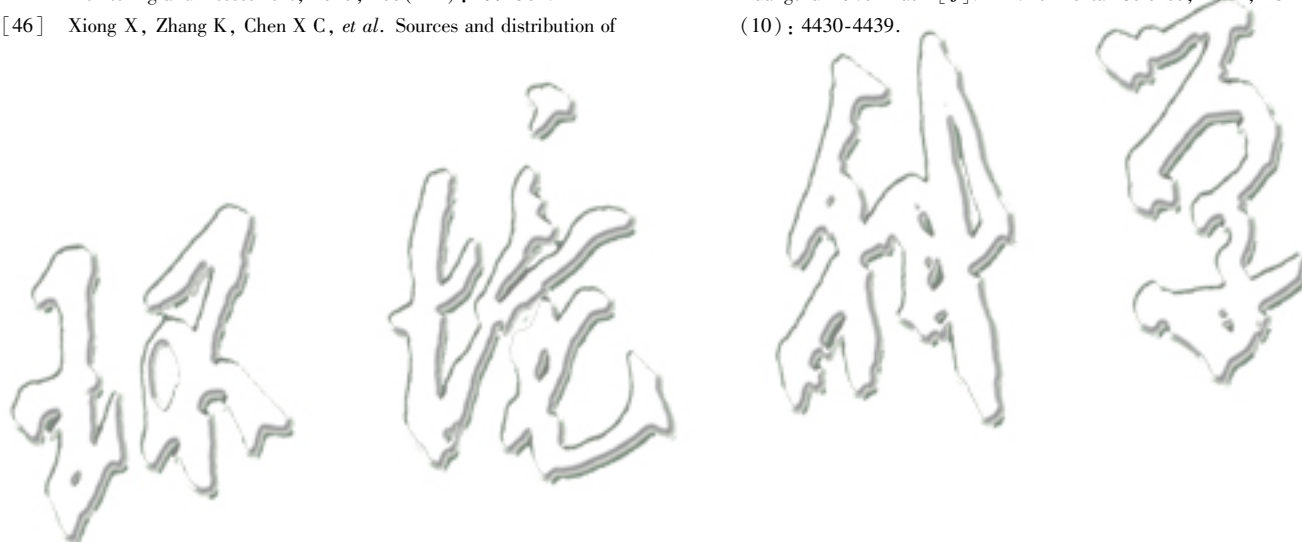
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CONTENTS

Impact of Climate Change on Summer Ozone in China	HU An-qi, XIE Xiao-dong, GONG Kang-jia, <i>et al.</i>	(1801)
Spatial-temporal Variation and Driving Factors of Ozone in China from 2019 to 2021 Based on EOF Technique and KZ Filter	WANG Hao-qí, ZHANG Yu-fen, LUO Zhong-wei, <i>et al.</i>	(1811)
Photochemical Mechanism and Control Strategy Optimization for Summertime Ozone Pollution in an Industrial City in the North China Plain	ZHENG Zhen-sen, DOU Jian-píng, ZHANG Guo-tao, <i>et al.</i>	(1821)
Spatiotemporal Evolution Characteristics of PM _{2.5} -O ₃ Compound Pollution in Chinese Cities from 2015 to 2020	NIU Xiao-xiao, ZHONG Yan-mei, YANG Lu, <i>et al.</i>	(1830)
Spatiotemporal Distribution Characteristics of Co-pollution of PM _{2.5} and Ozone over BTH with Surrounding Area from 2015 to 2021	SONG Xiao-han, YAN Li, LIU Wei, <i>et al.</i>	(1841)
Spatio-temporal Variation in PM _{2.5} Concentration and Its Relationship with Vegetation Landscape Patterns in Typical Economic Zones in China from 2000 to 2020	XU Yong, LI Xin-yi, HUANG Wen-ting, <i>et al.</i>	(1852)
Characteristics and Source Apportionment of Atmospheric Ion Deposition During Winter and Spring in the Core Area of Beijing	ZHAO Yu, LI Bei-bei, HUANG Yu-hu, <i>et al.</i>	(1865)
Input Characteristics of Dry Deposition of Atmospheric Particulates and Metals in Farmland in the Suburb of Nanjing	LIU Cui-ying, JIN Hao, FAN Jian-ling	(1873)
Pollution Characterizations and Oxidative Potentials of Water-Soluble Organic Matters at Different Polarity Levels in Winter PM _{2.5} Over Xi'an	LUO Yu, HUANG Sha-sha, ZHANG Tian, <i>et al.</i>	(1882)
Emission Characteristics of Organic Carbon and Elemental Carbon in PM ₁₀ and PM _{2.5} from Vehicle Exhaust and Civil Combustion Fuels	WANG Hong-lei, LIU Si-han, SUN Jie-juan, <i>et al.</i>	(1890)
Characteristics and Source Apportionment of PM _{2.5} in the Core Area of Ili River Valley in Spring	GU Chao, XU Tao, MA Chao, <i>et al.</i>	(1899)
Evaluation of Changes in PM _{2.5} Exposure Concentration and Health Risk for Urban Resident in Zhengzhou Based on High Spatial Resolution Grids	LI Yuan, XU Yi-fei, YUAN Ming-hao, <i>et al.</i>	(1911)
Emission Inventory of Building Material Industry in Henan Province Based on Multi-source Data Integration	LIU Xiao, HU Jing-nan, WANG Hong-mei, <i>et al.</i>	(1924)
Pollution Characteristics and Source Apportionment of Atmospheric Volatile Organic Compounds in Winter in Kaifeng City	SHI Yu-qi, ZHENG Kai-yun, DING Wei-ting, <i>et al.</i>	(1933)
Changes in O ₃ -VOCs-NO _x Sensitivity and VOCs Sources at an Urban Site of Nanjing Between 2020 and 2021	LU Xiao-bo, WANG Ming, DING Feng, <i>et al.</i>	(1943)
Variation Characteristics and Ozone Formation Potential of Ambient VOCs in Urban Beijing in Summer	ZHANG Rui, SUN Xue-song, WANG Yu, <i>et al.</i>	(1954)
Chemical Characteristics and Source Apportionment for VOCs During the Ozone Pollution Episodes and Non-ozone Pollution Periods in Qingdao	JIA Zhi-hai, GU Yao, KONG Cui-li, <i>et al.</i>	(1962)
Characteristics of O ₃ Production in the Western Suburb of Hefei in Summer Based on the Observation of Total Peroxy Radical	YU Hui, WEI Na-na, XU Xue-zhe, <i>et al.</i>	(1974)
Evaluation of Energy Saving and Carbon Reduction Effect of Air Pollution Prevention and Control Action Plan and Innovation Intermediary Effect	LI Shao-lin, WANG Qi-qi	(1985)
Scenario Simulation and Effects Assessment of Co-control on Pollution and Carbon Emission Reduction in Beijing	YU Shan, ZHANG Shuang, ZHANG Zeng-jie, <i>et al.</i>	(1998)
Simulation of Anthropogenic CO ₂ Emissions in the Yangtze River Delta Based on Different Emission Inventories	MA Xin-yi, HUANG Wen-jing, HU Ning, <i>et al.</i>	(2009)
Water Quality Change Trend and Risk Analysis of Wuhan Hanjiang River Water Source	ZHUO Hai-hua, LOU Bao-feng, XU Jie, <i>et al.</i>	(2022)
Pollution Characteristics and Risk Assessment of Antibiotics and Resistance Genes in Different Water Sources in the Wuhan Section of the Yangtze River	LI Bo-lin, ZHANG He, WANG Jun, <i>et al.</i>	(2032)
Occurrence Characteristics, Sources, and Toxicity Risk Analysis of Polycyclic Aromatic Hydrocarbons in Typical Rivers of Northern Shaanxi Mining Area, China	WU Xi-jun, DONG Ying, ZHAO Jian, <i>et al.</i>	(2040)
Spatio-temporal Characteristics of Organic Aggregates and the Driving Factors in Typical Lakes	XIE Gui-juan, GONG Yi, ZHU Fu-cheng, <i>et al.</i>	(2052)
Distribution Characteristics and Risk Assessment of Microplastics in Water of Different Functional Parks in Guilin	LI Pei-zhao, WU Li, HUANG Fei-fei, <i>et al.</i>	(2062)
Environmental Driving Factors and Assessment on the Aquatic Ecosystem of Periphytic Algae of Six Inflow Rivers in Yangtze River Basin	ZHANG Jing, HU Yu-xin, HU Sheng, <i>et al.</i>	(2072)
Influence and Driving of Environmental Heterogeneity on the Epilithic Diatom Community in Xiangxi River, a Tributary of the Three Gorges Reservoir Area	JI Lu-lu, ZHAO Lu, OUYANG Tian, <i>et al.</i>	(2083)
Characteristics of Phytoplankton Communities and Key Impact Factors in Three Types of Lakes in Wuhan	ZHANG Hao-kun, MIN Fen-li, CUI Hui-rong, <i>et al.</i>	(2093)
Effects of Heavy Metal Pollution on the Structure of Microbial Communities in Different Habitats	HE Yi-fan, XIAO Xin-zong, WANG Jia-wen	(2103)
Structure and Distribution Characteristics of Bacterial Community in Boqing River Water	WANG Sen, CHEN Jian-wen, ZHANG Hong, <i>et al.</i>	(2113)
Effects of Microplastic Exposure on the Community Structure and Function of Symbiotic Bacteria in <i>Sinularia microclavata</i>	LIU Min, CHE Wen-xue, ZENG Ying-xu, <i>et al.</i>	(2122)
Distribution Characteristics and Health Risk Assessment of Emerging Contaminants from Raw Water to Drinking Water in Shanghai	YAN Qi	(2136)
Adsorption Characteristics of Fluoride in Low-Concentration Water by Aluminum and Zirconium-Modified Biochar	LIU Yan-fang, GAO Wei, LIU Rui, <i>et al.</i>	(2147)
Sorption Characteristics and Site Energy Distribution Theory of Typical Estrogens on Microplastics	LIU Jiang-yan, ZHENG Mi-mi, HU Jia-wu, <i>et al.</i>	(2158)
Selection and Evaluation of Model Pollutants for Performance Assessment of Advanced Treatment of Industrial Park Wastewater by Ozonation	XIN Bo, SHAN Chao, LÜ Lu	(2168)
Identifying Driving Factors and Their Interacting Effects on Sources of Heavy Metal in Farmland Soils with Geodetector and Multi-source Data	ZHANG Hong-ze, CUI Wen-gang, LIU Sui-hua, <i>et al.</i>	(2177)
Pollution Characteristics and Source Apportionment of Heavy Metals in Farmland Soils Around the Gangue Heap of Coal Mine Based on APCS-MLR and PMF Receptor Model	MA Jie, SHEN Zhi-jie, ZHANG Ping-ping, <i>et al.</i>	(2192)
Contamination and Probabilistic Health Risk Assessment of Heavy Metals in Agricultural Soils Around a Lead-Zinc Smelter	HUANG Jian-bo, JIANG Deng-deng, WEN Bing, <i>et al.</i>	(2204)
Prediction of PAHs Content in Soil Around Gas Stations in Beijing Based on BP Neural Network	MA Sai-yan, WEI Hai-ying, MA Jin, <i>et al.</i>	(2215)
Spatial-temporal Distribution and Risk Assessment of Quinolones Antibiotics in Soil of Shijiazhuang City	ZHAO Xin-yu, CHEN Hui, ZHAO Bo, <i>et al.</i>	(2223)
Accumulation and Pollution Risks of Heavy Metals in Soils and Agricultural Products from a Typical Black Shale Region with High Geological Background	DENG Shuai, DUAN Jia-hui, NING Mo-huan, <i>et al.</i>	(2234)
Geochemical Characteristics of Cd in Different Parent Soils in Karst Area and Prediction of Cd Content in Maize	DAI Liang-liang, XU Hong-gen, GONG Hao, <i>et al.</i>	(2243)
Pollution Risk and Contribution Analysis of Pb, Cd, and As in Soils and Crops Under Different Land Use Types in Longyan City	WANG Rui, CHEN Nan, ZHANG Er-xi	(2252)
Influencing Factors of Cadmium Content in Wheat Grain: A Meta-analysis and Decision Tree Analysis	LIU Na, ZHANG Shao-bin, GUO Xin-yu, <i>et al.</i>	(2265)
Response Characteristics of Soil Organic Carbon Pool and Its Chemical Composition During Secondary Forest Succession in the Loess Plateau	LIU Han-yu, LIU Ying-yi, ZHANG Qi, <i>et al.</i>	(2275)
Effects of Short-Term Nitrogen and Phosphorus Addition on Soil Respiration Components in a Subalpine Grassland of Qilian Mountains	JIANG Yuan, GAN Xiao-ling, CAO Feng-feng, <i>et al.</i>	(2283)
Response of Soil Microbial Diversity to Long-term Enclosure in Degraded Patches of Alpine Meadow in the Source Zone of the Yellow River	YANG Peng-nian, LI Xi-lai, LI Cheng-yi, <i>et al.</i>	(2293)
Diversity and Predictive Functional of <i>Caragana jubata</i> Bacterial Community in Rhizosphere and Non-rhizosphere Soil at Different Altitudes	LI Yuan-yuan, XU Ting-ting, AI Zhe, <i>et al.</i>	(2304)
Effects of Simulated Acid Rain and Nitrogen Deposition on Soil Bacterial Community Structure and Diversity in the Masson Pine Forest	WANG Nan, QIAN Shao-yu, PAN Xiao-cheng, <i>et al.</i>	(2315)
Effects of Phosphogypsum and <i>Suaeda salsa</i> on the Soil Moisture, Salt, and Bacterial Community Structure of Salinized Soil	LIU Yue, YANG Shu-qing, ZHANG Wan-feng, <i>et al.</i>	(2325)
Effects of Combined Application of Fungal Residue and Chemical Fertilizer on Soil Microbial Community Composition and Diversity in Paddy Soil	GENG He-tian, WANG Xu-dong, SHI Si-bo, <i>et al.</i>	(2338)
Effects of Aeration on Surface Water Nutrient Dynamics and Greenhouse Gas Emission in Different Straw Returning Paddy Fields	HU Jin-hui, XUE Li-hong, QIAN Cong, <i>et al.</i>	(2348)
Effects of Exogenous Melatonin Treatment on the Growth and Antioxidant System of Rice Seedlings Under Antimony Stress	CHU Yu-tan, LI Yan, HUANG Yi-zong, <i>et al.</i>	(2356)
Life Cycle Prediction Assessment of Energy Saving and New Energy Vehicles for 2035	FU Pei, LAN Li-bo, CHEN Ying, <i>et al.</i>	(2365)
Distribution, Sources, and Behavioral Characteristics of Microplastics in Farmland Soil	BO Lu-ji, LI Bing, ZHANG Kai, <i>et al.</i>	(2375)
Research Progress on the Remediation Technology of Herbicide Contamination in Agricultural Soils	HU Fang-yu, AN Jing, WANG Bao-yu, <i>et al.</i>	(2384)
Research Progress and Prospect of Herbicide Residue Characteristics in Black Soil Region of China	LI Rui, WU Qiu-mei, ZHAO Gui-mei, <i>et al.</i>	(2395)