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# 气相色谱/质谱和红外光谱测定鱼体内微塑料

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**摘要**：为弥补现有光谱技术在检测微塑料方面的不足,全面了解野生海水鱼体内的微塑料赋存水平,本研究建立了热裂解-热脱附-气相色谱/质谱法(Py-TD-GC/MS),该方法在微塑料提取和量化方面具有优良的回收率(>90%),在此基础上,利用该方法定量渤海湾野生梭鱼和鲈鱼胃肠道中 PP、PE、PS 和 PVC 4 种微塑料(0.22~500μm)的质量浓度.结果发现,梭鱼胃肠道中小粒径微塑料(0.22~20μm)浓度((64.71±80.47)μg/g)明显低于鲈鱼((371.30±401.53)μg/g)($P$<0.05),而大粒径微塑料(20~500μm)浓度((150.33±116.58)μg/g)略高于鲈鱼((107±96.49)μg/g)($P$>0.05),且 PE 和 PVC 浓度均明显高于 PS 和 PP;接着使用激光红外成像系统(LDIR)定量渤海湾野生梭鱼和鲈鱼胃肠道中微塑料(20~500μm)丰度水平,发现检测到的微塑料粒径以 20~50μm 为主、形态以碎片为主、材质以 PE 和 PVC 等 11 种聚合物为主,并且梭鱼胃肠道中 PP、PE、PS 和 PVC 4 种微塑料的平均丰度((38.21±19.95)个/g)略高于鲈鱼((34.75±26.33)个/g)($P$>0.05),4 种材质微塑料质量浓度分布与颗粒丰度分布总体上一致.利用聚合物危害指数评估鲈鱼和梭鱼胃肠道中赋存微塑料的潜在生态危害,发现由于 PVC 微塑料的存在导致了较高的潜在危害指数.Py-TD-GC/MS 能够检测生物体内更小粒径微塑料,Py-TD-GC/MS 和红外光谱技术联用可全面揭示野生鱼类体内的微塑料污染特征.

**关键词**：管式炉裂解；热脱附；气相色谱/质谱；LDIR
**中图分类号**：X132 **文献标识码**：A **文章编号**：1000-6923(2025)07-4012-09

**Determination of microplastics in fish by gas chromatography/mass spectrometry and infrared spectroscopy.** YANG Ying[1,2], WU Yu-xuan[2,3], PAN Wei[2], ZHANG Zi-ye[2], AN Li-hui[2], GAO Jun-min[1*] (1.Key Laboratory of the Three Gorges Reservoir Region's Eco-Environment, Ministry of Education, Chongqing University, Chongqing 400045, China；2.State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China；3.College of Life Sciences, Hebei University, Baoding 071002, China). *China Environmental Science*, 2025,45(7)：4012~4020

**Abstract**：To address the limitations of conventional spectroscopic techniques in microplastic detection and comprehensively assess microplastic occurrence in wild marine fish, this study developed a pyrolysis-thermal desorption-gas chromatography/mass spectrometry (Py-TD-GC/MS) method. This approach demonstrated excellent recovery rates (>90%) for microplastic extraction and quantification. On this basis, this method was used to quantify the mass concentrations of PP, PE, PS and PVC (0.22~500μm) in the gastrointestinal tract of wild barracuda and bass in Bohai Bay. Results revealed that the concentration of small and medium-sized microplastics (0.22~20μm) in the gastrointestinal tract of barracuda ((64.71 ± 80.47) μg/g) was significantly lower than that of bass ((371.30 ± 401.53)μg/g) ($P$<0.05), while the concentration of large-sized microplastics (20~500μm) ((150.33±116.58) μg/g) was slightly higher than that in bass ((107±96.49) μg/g) ($P$>0.05). Additionally, the concentrations of PE and PVC were significantly higher than those of PS and PP. Subsequently, the laser infrared imaging system (LDIR) was used to quantify the abundance of microplastics (20~500μm) in the gastrointestinal tract of wild barracuda and bass in the Bohai Bay. It was found that the detected microplastics were mainly 20~50μm in size, primarily fragment-shaped, and mainly composed of 11polymers such as PE and PVC. The average abundance of PP, PE, PS and PVC in the gastrointestinal tract of barracuda ((38.21±19.95) items/g) was slightly higher than that of bass ((34.75±26.33) items /g) ($P$>0.05). The mass concentration distribution of microplastics in the four materials was generally consistent with the particle abundance distribution. The polymer hazard index was used to evaluate the potential ecological hazards of microplastics in the gastrointestinal tract of bass and barracuda, and it was found that the presence of PVC microplastics led to a higher potential hazard index. Py-TD-GC/MS can detect microplastics with smaller particle sizes in organisms, and the combination of Py-TD-GC/MS and infrared spectroscopy can fully reveal the characteristics of microplastic pollution in wild fish.

**Key words**：tube furnace pyrolysis；thermal desorption；gas chromatography mass spectrometry；LDIR

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微塑料在大气[1]、水体[2]和沉积物[3]等各种环境介质中广泛分布,且其污染水平与人类活动强度密切相关[4].微塑料体积小(粒径小于 5mm),易于被环境生物通过呼吸和食物等多个途径直接或间接摄入,同时微塑料表面吸附的环境污染物及其自身携带的各种功能添加剂在生物体内可能再次释放,进而对生物的生长、发育和繁殖产生不利影响[5-8].随着对微塑料环境分布与毒理效应认知的不断提升,微塑料污染的潜在生态危害与健康风险引起了全社会的广泛关注[9-10].

鱼类是水生态系统的关键组成,也是人体食物蛋白的主要来源之一,鱼体内微塑料的赋存情况及其潜在风险近年来也逐渐受到关注[11-13].现有研究揭示了全球鱼类体内微塑料污染的普遍性和空间差异性,主要表现为 3 个特征:(1)污染分布具有器官特异性,胃肠道微塑料丰度高于鳃器官(如 Pan 等[14]发现鱼类胃肠道中微塑料丰度(4.4 个/尾)明显高于鳃(2.2 个/尾));(2)类群间存在生物累积差异,鱼类的微塑料检出率和丰度高于贝类、甲壳类等无脊椎动物(Wang 等[15]证实鱼类检出率高出 25%,且微塑料丰度也明显高于沙蚕、贝类和甲壳类($P$<0.05));(3)区域污染水平不均衡,例如 Wootton 等[16]基于现有全球野生鱼体中微塑料的调查研究结果,发现有49%的调查鱼类样本中检出了微塑料(平均丰度为3.5 个/尾),其中北美地区鱼类体内微塑料丰度明显高于其他地区.这些研究结果有助于了解全球鱼体内微塑料污染水平,但均主要采用光谱法对粒径相对较大的微塑料颗粒(>20μm)进行表征,对于潜在危害更大的小粒径微塑料(<20μm)的赋存水平研究较少.

光谱法和质谱法是目前微塑料鉴定的主要方法,各自具有独特的优势和局限性.基于颗粒的光谱法,如傅里叶红外光谱(FTIR)[17]和激光红外光谱成像系统(LDIR)[18],能够直接提供微塑料的形状、大小、尺寸等多种形态学信息,这对于研究微塑料的来源、分布和环境影响具有重要意义.然而光谱法的空间分辨率受光的衍射极限影响,一般应用的检出限约为 20μm[19].基于质量的质谱法,例如热裂解气相色谱-质谱法(Py-GC/MS)[20]已被广泛用于定量水[21]、土壤[22]和生物[23]等环境样品中小粒径微塑料(<20μm)的污染水平.然而受仪器进样空间的限制,进样量少,导致定量线性范围通常在 1.0~20.0μg[22],甚至只有 0.01~2μg[24],难以适用于环境样品的定量分析.与之相比,利用热萃取解吸与气相色谱质谱联用(TED-GC/MS)[25]则可用于定量分析较高浓度的环境样品,但 350°C 的热解条件可能无法对 PVC 等高熔点聚合物进行准确定量[26].

为全面了解渤海湾野生鱼体内微塑料尤其小粒径微塑料污染水平,本研究首先对目前使用的 Py-GC/MS 和 TED-GC/MS 两种基于质量的质谱法进行改进,建立了管式炉热裂解-热脱附-气相色谱/质谱(Py-TD-GC/MS)方法,并利用该方法对鱼体内检出率较高的聚乙烯(PE)、聚丙烯(PP)、聚苯乙烯(PS)和聚氯乙烯(PVC)微塑料的质量浓度进行定量[27],随后利用 LDIR 分析了渤海湾野生梭鱼和鲈鱼胃肠道中微塑料颗粒赋存特征.利用 Py-TD-GC/MS 和 LDIR 分别从微塑料的质量浓度和颗粒丰度两个维度定量野生鱼体胃肠道组织中微塑料的赋存水平,为科学评估环境微塑料污染的生态危害和健康风险提供参考.

## 1　材料和方法

### 1.1　仪器与试剂

气相色谱-质谱联用仪(8890GC/5977B MSD,安捷伦公司,美国),气相色谱柱(250μm×1.4μm,30m,DB-624,安捷伦公司,美国);热脱附解析仪(Markes TD100-xr,玛珂思仪器(上海)有限公司);热重分析仪(RT-1100℃,TGA2STAR System,梅特勒托利多科技(中国)有限公司);高温管式裂解炉(OTF-1000X- SS,杭州卓驰仪器有限公司);激光红外成像系统(LDIR 8700,安捷伦科技有限公司,美国)和傅里叶变换红外光谱仪(FTIR 630,安捷伦科技有限公司,美国).

PP(粒径 10μm,密度 0.90~0.91g/cm$^3$)、PS(粒径 10μm,密度 1.04~1.09g/cm$^3$)和 PVC(粒径 10μm,密度 1.38g/cm$^3$)均购自中国东莞市特塑朗化工原料有限公司,PE(粒径 13μm,密度 0.91~0.92g/cm$^3$)购自上海麦克林生化科技有限公司,分析纯 KOH(纯度≥90%)和甲酸钾(纯度≥96%)(上海麦克林生化科技有限公司),甲醇和丙酮(农残级,纯度≥99.9%)(Thermo Fisher Scientific 公司,美国),玻璃纤维滤膜(孔径 0.22μm)(上海兴亚净化材料厂),不锈钢滤膜(孔径 20μm)(九鼎高科过滤设备(北京)有限公司).

### 1.2 样品采集

利用拖网采集渤海湾野生鲈鱼[平均体长(79.33±3.33) cm;平均体重(4341.67±196.00) g]和梭鱼[平均体长(39.43±0.99) cm;平均体重(594.60±54.2)9g],铝箔包裹后带回实验室-20℃冷冻备用.在超净台解冻鱼样品并使用超纯水清洗.由于鲈鱼个体较大,肠胃道分离,故分别取样,而梭鱼胃肠道难以分离,故混合匀浆备用.

### 1.3 Py-TD-GC/MS 定量微塑料质量浓度

**1.3.1 样品前处理** 取新鲜胃肠道组织置于石英研钵中研磨至糜状混匀,然后称取 1.0g(湿重)转移至250mL 烧杯中并按 1:30(*W*/*V*)加入新鲜配制的 KOH 溶液(10%),移至恒温摇床中((50.0±0.5)℃)消解24h(180r/min).将消解液全部过 0.22μm 玻璃纤维膜后用超纯水清洗烧杯内壁 3 次,将清洗液也一并过同一张滤膜.向滤膜上依次加入 20mL 甲醇和 20mL 丙酮,保持自然滴下,并在滴完后真空抽滤至近干.取下滤膜对折两次并用铝箔纸包裹,随后置于恒温箱中((50.0±0.5)℃)烘干.

**1.3.2 样品测定** 将烘干的玻璃纤维膜置于石英管中,在 550℃下进行热裂解.裂解产物在氦气流(100mL/min)吹扫下被吸附管捕集,这一过程持续60min.将吸附管转移到热脱附仪中,并在 300℃条件下解析10min.脱附的裂解产物被氦气吹扫进入冷阱,并以 82:1 的分流比进入气相色谱系统:35℃,保持5min;以 10℃/min 升温至 260℃,保持 10min.质谱仪离子温度 230℃,电压为 70eV,全扫描模式采集数据(35~350amu).

### 1.4 LDIR 定量微塑料颗粒丰度

根据课题组前期建立的 LDIR 方法[28]测定鱼样品中微塑料丰度,具体步骤如下:称取 5g(湿重)胃肠道组织同 Py-TD-GC/MS 前处理方法进行消解后将消解液相继过 500 和 20μm 孔径的不锈钢滤膜.其中,500μm 孔径不锈钢滤膜置显微镜下观察,并利用630FTIR 对膜上颗粒物材质进行逐一鉴定;20μm 孔径不锈钢滤膜转移并悬挂在 250mL 三角瓶中,随后加入甲酸钾溶液浸没滤膜,超声 30min 后静置 12h,静待微塑料等颗粒物悬浮至溶液表面;随后向三角瓶中加入过量甲酸钾溶液,利用烧杯接取从三角瓶上部溢出的含有微塑料的甲酸钾溶液,并将溢出的甲酸钾溶液再次过 20μm 孔径不锈钢滤膜.此过程重复 3 次,并将全部溢出溶液过滤至同一张滤膜上.随后,将滤膜转移至含有无水乙醇的玻璃浓缩管中并完全浸入,超声 30min,移出滤膜,随后将无水乙醇氮吹至近干,并用无水乙醇定容至 0.5mL.将含有微塑料的无水乙醇均匀滴在反射玻片上,置于超净台内待无水乙醇完全挥发;然后将玻片转移至 8700LDIR 样品台,在 975~1800cm$^{-1}$ 测试所有颗粒材质、数量、粒径及形态等.

### 1.5 质量控制

为减小背景干扰,本研究取样和前处理所有操作均在实验室通风柜内进行.实验过程中严格禁止使用塑料工具,包括塑料自封袋、量筒等,并用超纯水清洗玻璃烧杯等工具不少于 3 遍.另外,所有溶剂包括超纯水在使用前均过 0.22μm 的玻璃纤维膜以去除可能存在的微塑料背景污染.玻璃纤维膜在使用前经过 500℃加热处理 30min.且本研究在处理鱼组织样品的同时处理 6 个空白样品用于监测背景污染.

### 1.6 鱼体微塑料暴露风险

考虑到微塑料聚合物材质单体的潜在危害,本研究进一步利用聚合物单体的危害指数(PHI)[29]评估鱼体内微塑料污染的潜在危害,公式如式(1).

$$\mathrm{PHI} = \sum P_n \cdot S_n \tag{1}$$

式中:$P_n$ 是样品中微塑料聚合物类型百分比;$S_n$ 是微塑料中聚合物单体危险指数.

## 2 结果与讨论

### 2.1 Py-TD-GC/MS 定性定量鱼体组织中微塑料方法的建立

根据每种聚合物裂解产物质谱响应强度、特异性及其线性关系,分别筛选并确定了鱼体内广泛存在的 PP、PE、PS 和 PVC 4 种微塑料对应的特异指示化合物.其中,2,4-二甲基-1-庚烯(*m*/*z* 70)是 PP 的指示化合物,1-十二烯(*m*/*z* 83)作为 PE 的指示化合物,苯乙烯(*m*/*z* 104)作为 PS 的指示化合物,苯(*m*/*z* 128)作为 PVC 的指示化合物.同时利用每种聚合物微塑料裂解产物的特异指示化合物建立了定量曲线,线性范围内质量浓度和响应关系的相关系数均大于 0.99(图 1),特别是 PE 的线性范围达到了 3~1800μg,这一范围明显优于其他采用 Py-GC/MS 方法的研究,例如江竹莲等[22]使用 Py-GC/MS 对土壤

中 PP、PE、PS、PET 进行定量时,其线性范围仅在 1.0~20.0μg.在此基础上,进一步确定了仪器检测限(IDL=3×信噪比)和方法检出限(LOD=3.14×测试 7 次虾肌肉空白基质的标准偏差),具体数值见表 1.

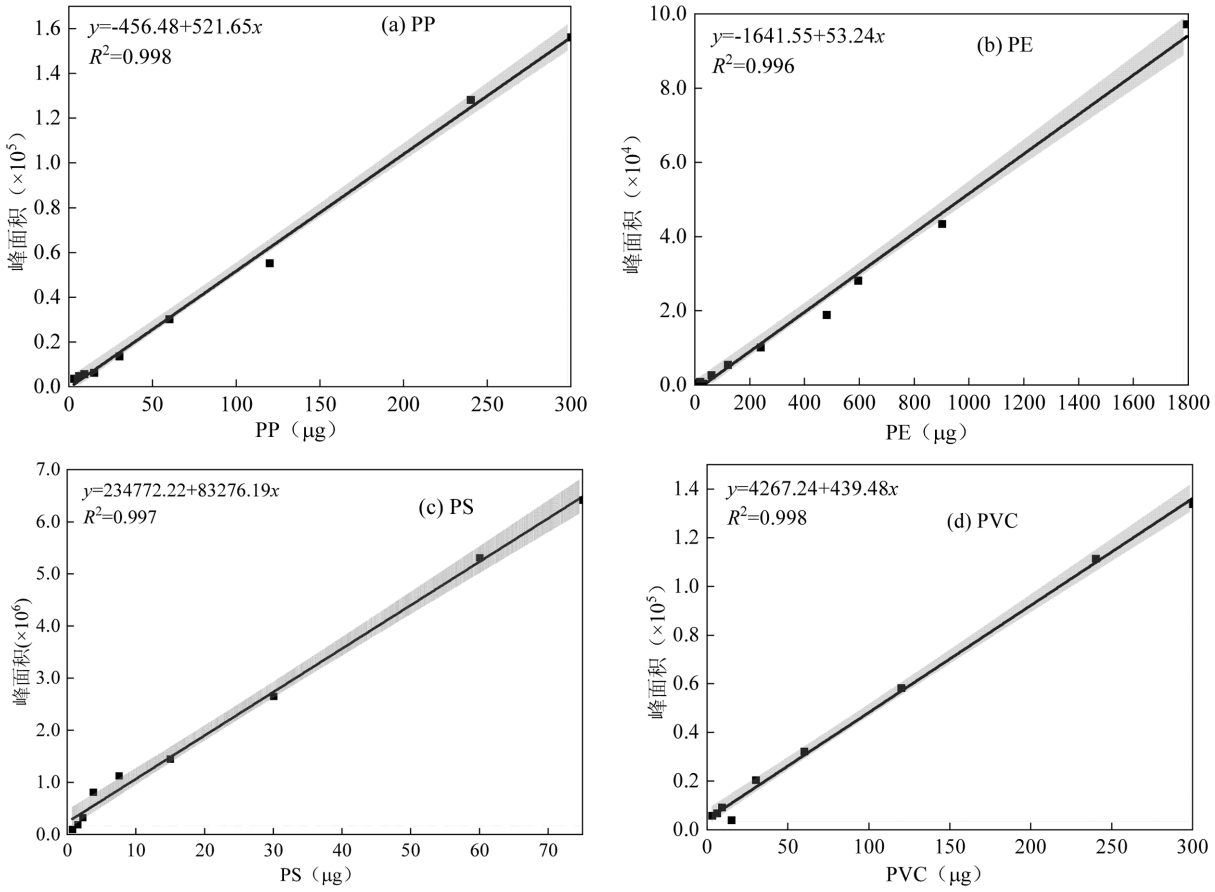



图 1　4 种微塑料的标准曲线

Fig.1　Quantification of four microplastics standard curves

**表 1　微塑料指示化合物、仪器检测限(IDL)和方法检出限(LOD)**

Table 1　Microplastics indicator compounds, instrument detection limits (IDL), and method detection limits (LOD)

| 聚合物 | 定性化合物 | 定量离子(*m*/*z*) | 保留时间(min) | IDL(μg/g) | LOD(μg/g) |
|---|---|---|---|---|---|
| PP | 2,4-二甲基-1-庚烯 | 70 | 12.525 | 0.31 | 3.47 |
| PE | 十二烯 | 83 | 18.977 | 0.72 | 7.97 |
| PS | 苯乙烯 | 104 | 14.154 | 0.025 | 0.17 |
| PVC | 萘 | 128 | 19.901 | 0.16 | 5.21 |

为进一步验证方法的可靠性和准确性,称取 1.0g 去除消化道及内膜的南美白对虾肌肉并分别加入 45.0,120.0 及 240.0μg 的 PP 和 PVC,60.0,240.0 及 480.0μg 的 PE,11.25,30.0 及 60.0μg 的 PS 进行微塑料的加标回收实验(*n*=6),计算每种微塑料定量方法回收率.

**表 2　Py-TD-GC/MS 定量目标微塑料的回收率与精密度**

Table 2　Recovery and precision of Py-TD-GC/MS quantification of target microplastics

| 聚合物 | 加标(μg/g) | 回收率(%) | RSD(%) |
|---|---|---|---|
| PP | 45 | 90.32±14.14 | 15.15 |
| | 120 | 128.1±8.51 | 6.58 |
| | 240 | 123.64±16.7 | 13.45 |
| | 平均 | 114.02±4.19 | 11.73 |
| PE | 45 | 99.55±21.25 | 19.42 |
| | 240 | 141.03±34.52 | 24.16 |
| | 480 | 135.07±12.89 | 9.48 |
| | 平均 | 125.22±10.91 | 17.69 |
| PS | 11.25 | 101.99±6.13 | 5.96 |
| | 30 | 103.66±4.41 | 4.24 |
| | 60 | 113.55±5.08 | 4.47 |
| | 平均 | 106.4±0.87 | 4.89 |
| PVC | 45 | 92.19±15.26 | 13.85 |
| | 120 | 111.53±15.43 | 13.04 |
| | 240 | 117.43±14.72 | 12.19 |
| | 平均 | 107.05±0.37 | 13.03 |

结果如表 2 所示,定量 4 种微塑料加标回收率分

别为(114.02±4.19)%(PP)、(125.22±10.91)% (PE)、(106.4±0.87)%(PS)、(107.05±0.37)%(PVC),并且 3 种不同浓度加标回收率的重现性为 4.89%~ 17.69%,说明 Py−TD−GC/MS 可用于准确定量环境生物组织样品中目标微塑料的浓度水平.

### 2.2 渤海湾野生鱼体内微塑料质量浓度

在野生梭鱼和鲈鱼的胃肠道均检出了不同浓度的目标微塑料.其中,鲈鱼胃肠道中小粒径微塑料(0.22~20μm)的平均浓度((371.30±401.53)μg/g)显著高于梭鱼胃肠道中小粒径微塑料的平均浓度((64.71±80.47)μg/g)($P$<0.05)(图 2(a)),但梭鱼胃肠道中大粒径微塑料(20~500μm)的平均浓度((150.33±116.58) μg/g)略高于鲈鱼((107±96.49) μg/g)($P$>0.05)(图 2(b)).造成这种差异的原因可能是由于鲈鱼(肉食性)具有较强消化能力,进而能够很快将摄入的大粒径微塑料快速消化破碎成更小粒径(<20μm)微塑料,从而导致小粒径微塑料浓度较高.此外,鲈鱼在食物链中的营养级要高于梭鱼,已有研究表明微塑料丰度与营养级呈正相关[10],这意味着小粒径微塑料可能会通过营养级传递累积导致鲈鱼体内含量更高.

图 3(a、b)显示,鲈鱼肠道(90.34%)和胃(74.35%)中小粒径微塑料质量浓度占比均较高,其中鲈鱼肠道中小粒径微塑料的浓度(Σ172.85μg/g)甚至是大粒径微塑料(Σ18.47μg/g)9 倍以上,说明了大粒径微塑料被生物摄入后会在体内被进一步消化破碎成小粒径颗粒.海洋轮虫[30]、南极磷虾[31]、斑海豹[32]体内微塑料颗粒丰度的变化也证实了这一猜测.Roch 等[33]甚至指出有超过 95%的微塑料可能小于 40μm.值得注意的是,随着大粒径微塑料进一步破碎成更小粒径的颗粒,因其比表面积增加,从而吸附能力增加,导致从环境甚至生物体内吸附污染物如增塑剂、多溴联苯醚(PBDE)、重金属、多氯联苯(PCB)等潜力增大[34],进而引发颗粒摩擦损伤与污染物化学毒性的协同效应[35],有可能对生物体产生更大的毒害作用.

在定量的 4 种微塑料中,PE 是占比最大的材质,其次是 PVC,PP 和 PS 的含量较低,这与现有研究结果一致[36-39].PE 是应用较广的通用塑料之一,被大量用于塑料袋、食品容器、家用塑料瓶和塑料薄膜等,但因其回收价值低而回收成本高,导致大量的 PE 塑料废弃物被丢弃进入环境,其在环境中破碎从而产生大量的 PE 微塑料,造成环境中 PE 微塑料污染普遍[40].同样,PVC 也是五大通用塑料之一[41],广泛用于输水管道、包装、桌布、窗帘、充气玩具等日常生活,从而造成了环境中 PVC 微塑料污染.

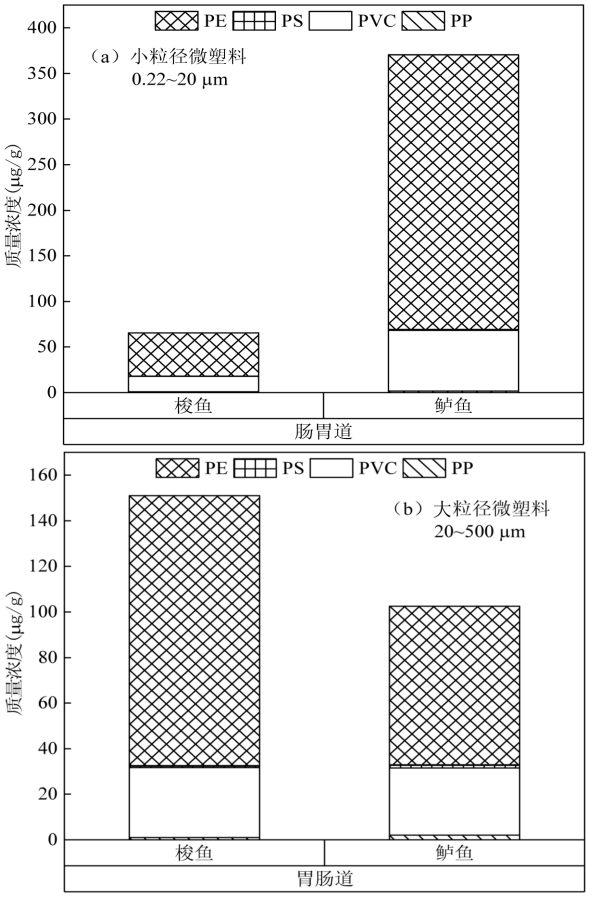
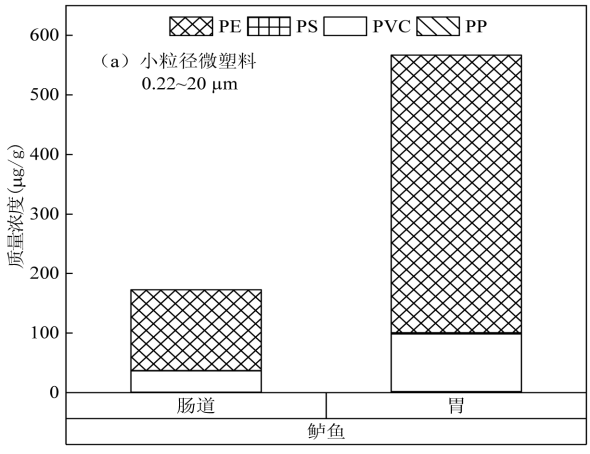



图 2 梭鱼和鲈鱼胃肠道中目标微塑料浓度

Fig.2 Target microplastic concentrations in the gastrointestinal tract of barracuda and sea bass



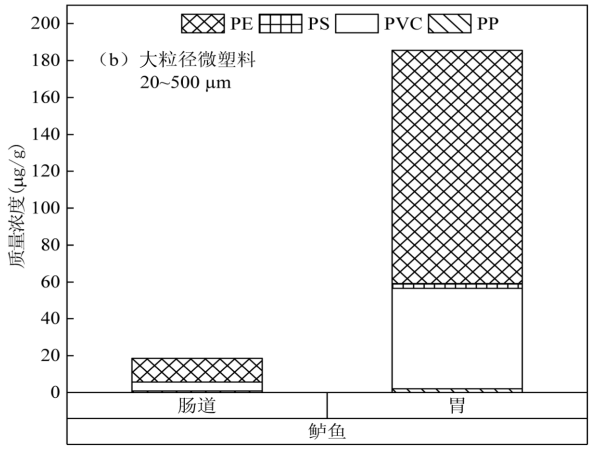



图 3　鲈鱼胃和肠道中目标微塑料浓度

Fig.3　Target microplastic concentrations in the stomach and intestine of sea bass

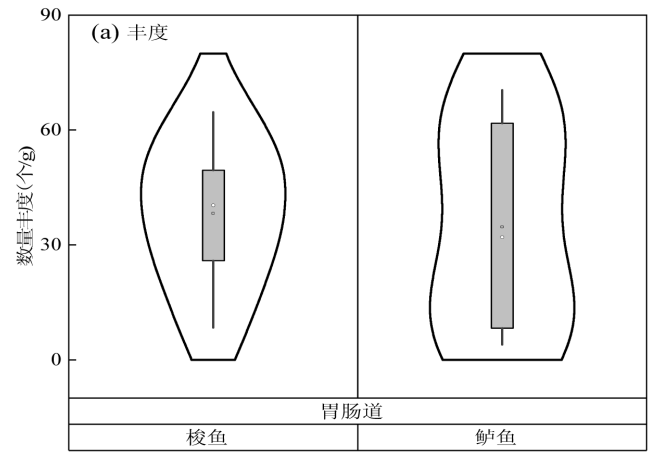
## 2.3　渤海湾野生梭鱼和鲈鱼体内微塑料颗粒丰度

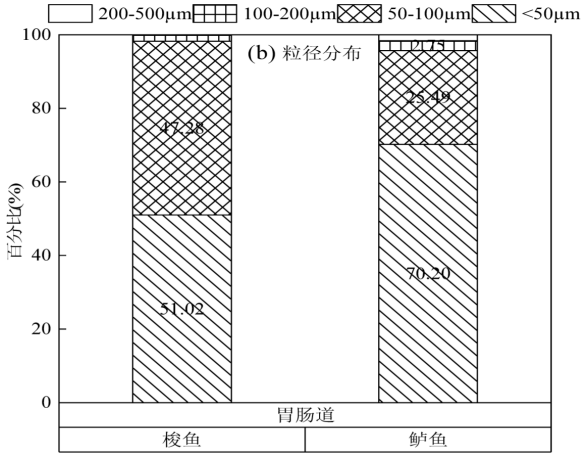
由图 4 可见,在采集的鲈鱼和梭鱼样本中,微塑料的检出率为 100%,检出了 PP、PE、PS、PVC、聚对苯二甲酸乙二醇酯(PET)、聚酰胺(PA)等 11 种聚合物材质的微塑料,粒径范围为 20.34~346.99μm,并且粒径越小占比越高,这与 Py-TD-GC/MS 表征结果一致.另外,所有微塑料均以碎片为主,同时还有薄膜、颗粒和纤维.

两种鱼胃肠道中 PP、PE、PS 和 PVC 4 种微塑料的颗粒丰度如图 4(a)所示.其中梭鱼胃肠道中微塑料平均丰度为(38.21±19.95)个/g,略高于鲈鱼胃肠道中微塑料的平均丰度(34.75±26.33)个/g($P$>0.05),这与 Py-TD-GC/MS 表征中梭鱼胃肠道中微塑料(20~500μm)的平均浓度略高于鲈鱼胃肠道中微塑料平均浓度的结果相一致.这可能与梭鱼的杂食性及其主要在近岸活动有关.研究表明,鱼类摄入塑料的频率受其距离海岸的远近影响,近岸生物摄入微塑料的频率通常高于远岸生物[42].在鲈鱼和梭鱼胃肠道中检出的微塑料均以粒径 20~50μm 的颗粒为主(图 4(b)),这与其它研究报道 20~50μm 微塑料占全部检出微塑料近 50%的结果类似[43].另外,碎片在所有检出微塑料中占主导地位(梭鱼胃肠道:(56%±14%);鲈鱼胃肠道(44%±13%))(图 4(c)),这也与其它鱼类体内检出微塑料的形态占比一致[41,44-45].

通过 LDIR 对两种鱼胃肠道样品检测并对比数据库后,主要检出的 PP、PE、PS 和 PVC 4 种微塑料的激光红外光谱如图 5 所示.这 4 种微塑料在鲈鱼胃肠道中分布比例如图 4(d)所示,PVC 和 PE 是检出各种材质微塑料的主要材质类型,这与 Py-TD-GC/MS 的检出结果一致.与 Py-TD-GC/MS 不同的是,梭鱼胃肠道中 PP 也有大量检出,这可能与不同微塑料粒径大小和聚合物密度有关.因此单纯以微塑料颗粒丰度推测质量浓度可能会存在明显误差[37].

对比两种微塑料检测方法,Py-TD-GC/MS 定性能力强、灵敏度高,在小粒径微塑料的定量方面具有优越性;LDIR 受仪器能力限制虽无法准确定量小粒径微塑料,但能同时识别多种材质的微塑料(>20μm),提供丰富的形态学信息.在实际应用中,如果需要同时获取微塑料的化学成分和形态学信息,可以将 Py-TD-GC/MS 和 LDIR 方法结合使用,以提高检测的全面性和准确性,有助于更全面地理解微塑料的环境行为和生态影响.



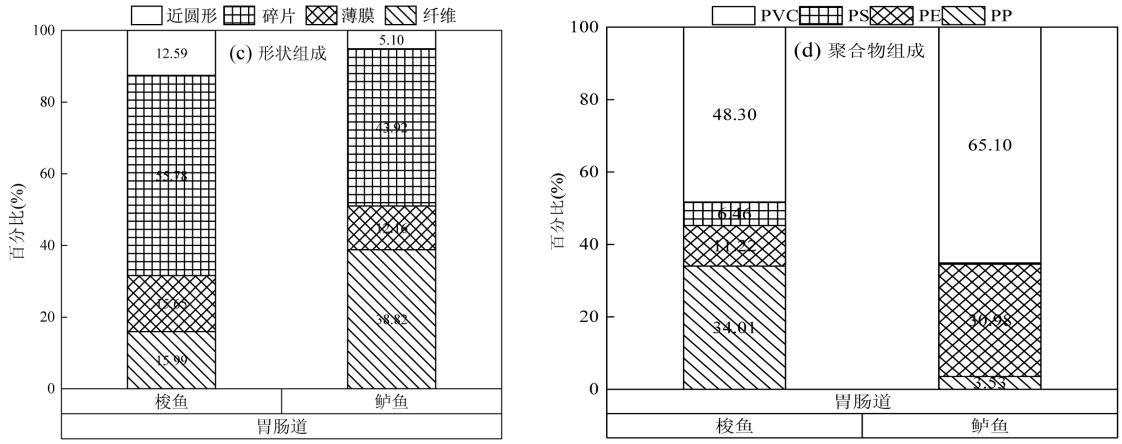



图 4 梭鱼和鲈鱼胃肠道中微塑料 LDIR 检测结果

Fig.4 LDIR detection results of microplastics in the gastrointestinal tract of barracuda and sea bass

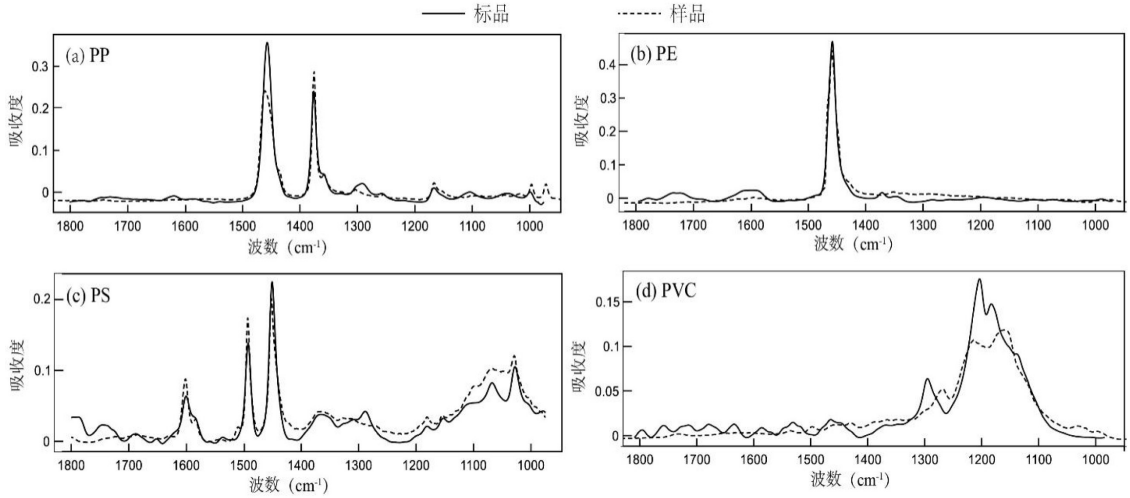



图 5 鲈鱼和梭鱼胃肠道中典型微塑料样品的激光红外成像光谱

Fig.5 Laser infrared imaging spectra of typical microplastic samples in the gastrointestinal tract of sea bass and barracuda

## 2.4 野生鱼体内微塑料暴露危害

基于在梭鱼和鲈鱼胃肠道中检出的小粒径微塑料的材质类型和质量浓度,进一步利用 PHI 评估目标微塑料对生物体的潜在健康危害.评估结果显示,梭鱼胃肠道中微塑料的潜在健康危害指数(PHI=2640)高于鲈鱼胃肠道中微塑料的潜在健康危害指数(PHI=1795)(表 3).这一结果明显高于 Nithin 等[46]对于印度东南沿海受微塑料污染的鱼的潜在危害评估结果(1<PHI<10),但低于 Fang 等[47]对福建市售海水鱼的评估结果(1 < PHI<5000).进一步分析表明,这是由于本研究中 PVC 单体的氯乙烯(VC)具有高毒性指数,因而导致渤海湾野生的梭鱼和鲈鱼具有较高的 PHI.这种潜在危害指数有助于更全面地了解微塑料污染的潜在生态危害和健康风险,为后期有针对性开展治理提供科学依据.

**表 3 梭鱼和鲈鱼胃肠道中靶向微塑料的潜在危害评估**

Table 3 Assessment of potential hazards of targeted microplastics in the gastrointestinal tract of barracuda and perch

| 样品名称 | 聚合物 | 质量百分比(%) | 单体危害值* | PHI** | 危害分级** | 危害分类** |
|---|---|---|---|---|---|---|
| 梭鱼胃肠道 | PP | 0.5 | 1 | 0.00 | I(0~1) | 低风险 |
| | PE | 72.8 | 11 | 8.00 | II(1~10) | 中等风险 |
| | PS | 0.4 | 30 | 0.13 | I(0~1) | 低风险 |
| | PVC | 26.3 | 10001 | 2631.42 | V(>1000) | 极其危险 |
| 鲈鱼胃肠道 | PP | 0.8 | 1 | 0.01 | I(0~1) | 低风险 |
| | PE | 81.1 | 11 | 8.92 | II(1~10) | 中等风险 |
| | PS | 0.3 | 30 | 0.08 | I(0~1) | 低风险 |
| | PVC | 17.9 | 10001 | 1786.18 | V(>1000) | 极其危险 |

注:“*”参照文献[48];“**”参照文献[29].

需要指出的是,环境微塑料污染的潜在生态危害和健康风险与多个因素有关,如微塑料粒径、材质类型、形状、含有的添加剂及其表面吸附的污染物等.因此,未来还需基于更多实验的研究进一步阐明各种因素的单独和协同作用,以更科学更准确地评估环境微塑料污染的潜在生态效应和健康风险,从而为环境微塑料污染精准治理提供科学依据.

## 3　结论

3.1　渤海野生梭鱼和鲈鱼胃肠道中检出的微塑料以小粒径为主(<50μm),以及材质以 PVC 和 PE 为主.

3.2　梭鱼胃肠道中大粒径微塑料(20~500μm)颗粒丰度((38.21±19.95)个/g)和质量浓度((150.33±116.58)μg/g)与鲈鱼((34.75±26.33)个/g 和((107±96.49)μg/g)相近,但小粒径微塑料(0.22~20μm)平均浓度((64.71±80.47)μg/g)明显低于鲈鱼((371.30±401.53) μg/g).

3.3　LDIR 和 Py−TD−GC/MS 在定量环境微塑料中各具优势,其中 LDIR 能够同时识别多种材质的微塑料(>20μm),而 Py−TD−GC/MS 能够定量小粒径微塑料(>0.22μm)污染水平,可作为技术互补同时从颗粒丰度和质量浓度两个方面共同表征环境微塑料的污染水平和赋存特征,进而为全面评估微塑料的生态危害和健康风险提供可靠数据支撑.

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