Eco-Environmental Knowledge Web

生态毒理学报
Asian Journal of Ecotoxicology

第 17 卷 第 2 期 2022 年 4 月
Vol. 17, No.2 Apr. 2022

DOI: 10.7524/AJE.1673-5897.20210105001
赵培强, 吴志丰, 董四君, 等. 基于文献计量方法的微塑料在鱼体中的污染现状及毒性效应研究进展[J]. 生态毒理学报,2022, 17(2): 43-63
Zhao P Q, Wu Z F, Dong S J, et al. Research progress of contamination and toxic effects of microplastics in fish based on a statistical analysis of patterns of publications [J]. Asian Journal of Ecotoxicology, 2022, 17(2): 43-63 (in Chinese)

基于文献计量方法的微塑料在鱼体中的污染现状及毒性效应研究进展

赵培强[1,2]，吴志丰[1]，董四君[3,#]，黄乾生[1,*]

1. 中国科学院城市环境研究所中国科学院城市环境与健康重点实验室,厦门 361021
2. 中国科学院大学,北京 100049
3. 河北大学生命科学学院,保定 071002

收稿日期:2021-01-05　　**录用日期:**2021-04-23

摘要: 微塑料污染作为全球性的环境问题,越来越受到人类的关注。每年有大量微塑料进入水环境,因此水生生物正面临着由微塑料带来的巨大威胁,特别是作为水生生态系统重要组成部分及人类重要食物来源的鱼类。前期调查数据显示全球范围内渔业资源逐年减少的同时,鱼类受到的微塑料污染正在不断加剧。随着分析检测水平的提高和生物学实验技术的发展,微塑料对鱼类影响的研究特别是其毒性效应研究越来越多,而且涉及的内容越来越广泛。本文基于文献计量学方法概述了目前微塑料对鱼类影响的几个主要方面。(1)全球鱼类受微塑料污染的现状(鱼类受到的污染程度、受污染鱼类体内的微塑料特征)。(2)微塑料对鱼类产生毒性效应的相关要素:暴露方式(长期/短期、急性/慢性、单一/联合)、微塑料特征(种类、大小、形状、浓度等)、鱼类的生理变化(生殖、免疫、生长、代谢、行为等)、受影响的器官(肝脏、消化道、鳃等)、微塑料的归趋(积累、转移等)。(3)存在问题与展望:缺乏统一的环境分析方法和标准化的毒性测试方法、暴露研究在符合环境实际的同时还应考虑塑料添加剂的影响、加强微塑料的生态风险评估。

关键词: 微塑料;鱼类;污染现状;毒性效应
文章编号: 1673-5897(2022)2-043-21　　**中图分类号:** X171.5　　**文献标识码:** A

Research Progress of Contamination and Toxic Effects of Microplastics in Fish Based on a Statistical Analysis of Patterns of Publications

Zhao Peiqiang[1,2], Wu Zhifeng[1], Dong Sijun[3,#], Huang Qiansheng[1,*]
1. Key Laboratory of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, China
2. University of Chinese Academy of Sciences, Beijing 100049, China
3. College of Life Science, Hebei University, Baoding 071002, China
Received 5 January 2021　　**accepted** 23 April 2021

Abstract: As a global environmental problem, microplastics (MPs) have attracted increasing attention of humans. Each year there were a large number of MPs enter the water environment, the aquatic organisms are facing huge

基金项目:国家重点研发计划项目(2018YFE0103300);国家自然科学基金面上项目(21777158)
第一作者:赵培强(1986—),男,博士研究生,研究方向为生态毒理学,E-mail: 1058135594@qq.com
* **通讯作者**(Corresponding author), E-mail: qshuang@ iue.ac.cn
\# **共同通讯作者**(Co-corresponding author), E-mail: sjdong@hbu.edu.cn

threats posed by MPs, especially fish, which are an important part of aquatic ecosystems and an important food source for humans. Previous surveys showed that fishery resources were decreasing year by year while the influences of MPs on fish were increasing all over the word. With the improvement of analysis and detection level and the development of biological experimental technology, more and more studies have been done on the effects of MPs on fish, especially on their toxic effects, which involve more and more extensive aspects. In this paper, the main aspects on the influence of MPs on fish is comprehensive summarized based on a statistical analysis of the patterns of publications. Firstly, the contamination posed by MPs on fish all over the word (polluted condition of fish all over the word, MPs characteristics in contaminated fish). Secondly, the main elements of toxic effects of MPs on fish, including exposure styles (long-time or short-time, acute or chronic, single or combined), MPs characteristics (type, size, shape and concentration, etc.), physiological changes of fish (reproduction, immunization, growth, metabolism and behavior, etc.), the organs affected (liver, intestine, gill, etc.), the fates of MPs ingested by fish (accumulation, transfer, etc.). Thirdly, the problems and perspectives, including lack of unified environmental analysis methods and standardized toxicity testing methods, exposure studies which should not only accord with the environmental reality, but also consider the impact of plastic additives, and strengthening the ecological risk assessment of MPs.

Keywords: microplastics; fish; contamination condition; toxic effect

“微塑料(MPs)”是指<5 mm的微型塑料碎片[1],20世纪70—80年代已有科学家关注塑料碎屑在环境中的变化及其对环境的影响[2],但直到2004年题为“Lost at sea: Where is all the plastic?”的文章[3]在Science杂志上发表后微塑料才开始引起科学家们的广泛关注。之前的报告指出,全球塑料垃圾产生量和处置量呈指数增长趋势[4]。有文献统计发现,目前全球主要的淡水生态系统均受到不同程度的微塑料污染,微塑料浓度为100~3 500个·L^{-1}[5]。另有研究估算,每年大约有200万t不同来源的微塑料纤维被释放到海洋中[6]。塑料污染已成为一个全球性问题,特别是对全球水环境的污染及水生生物多样性的影响[7]。有学者通过文献计量学综述了全球微塑料的研究情况,发现MPs与freshwater(淡水)、marine debris(海洋碎片)、fish(鱼)都存在大量共现关系(co-occurrence)[8],说明越来越多的研究关注微塑料与鱼类的相互关系。

鱼类作为水生生态系统的重要组成部分,对生态系统稳定具有重要意义。同时,鱼类为人类提供大量蛋白质,特别是海洋鱼类,它们为世界上2/3的人口提供了40%的蛋白质[9]。历史数据显示,自20世纪70—80年代,随着捕捞技术的进步、捕捞强度的增大,海洋渔业资源开始衰退[10]。有学者通过计算渔业捕捞的主要鱼种的营养级变化,在印度[11]与巴西[12]都发现自20世纪70—80年代以来,主要鱼获的营养级呈下降趋势,这表明,高营养级鱼类无法通过自然补充满足人类对鱼类的需求,低营养级鱼种面临逐渐增加的捕捞压力。微塑料具有持久性、疏水性等特点,且大小与各种浮游生物相似,很容易被滤食性水生生物误食,这增加了微塑料在食物网中积累及营养转移的潜在风险[13]。已有大量研究关注水生生物与微塑料之间的相互关系,而且越来越多的证据表明微塑料可能对暴露的生命体产生重大的健康影响[14]。有研究通过微塑料为主的关键检索词在Google Scholar数据库中进行检索,发现47%的文章是关于微塑料对生物的影响[15]。就鱼类而言,它们既可以直接摄入水中的微塑料也可以通过捕食其他生物获得微塑料,因此鱼类面临很大的暴露风险。目前以微塑料及鱼类为研究内容开展的研究有很多,我们基于Web of Science核心数据库,利用布尔运算符“TS=Microplastic and TS=fish”检索后,统计全球以微塑料及鱼类为研究对象的主要国家,发现目前在全球范围内,不同国家对微塑料与鱼类相互关系的关注度差别很大,研究内容主要集中在野外调查鱼类摄取微塑料的情况和微塑料对鱼类的影响,特别是微塑料对鱼类的毒性效应。目前,关于微塑料对鱼类产生毒性效应的文献有很多,目前的研究大致可以概括为:研究人员使用不同特征(类型、大小、形状、浓度)的微塑料,采用不同暴露途径(食物相、水相),开展了不同暴露时间(短期/急性、长期/慢性)、不同暴露形式(单一暴露、联合暴露)的多项研究。这些研究主要关注了微塑料对鱼类的生理

活动(生殖、免疫、生长、代谢、行为等)、组织器官(肝脏、肠道、鳃等)的影响及鱼体中微塑料的归趋(排泄、转移、传递)等。由于相关研究中涉及的要素很多,因此缺乏关于微塑料对鱼类影响的全面概述。

虽然已有文献分别综述了淡水、海洋中鱼类对微塑料摄取情况[16-17],但关于全球水生生态系统中鱼类受到微塑料污染现状的全面概括尚未见报道。综上,本文基于 Web of Science 文摘数据库,利用 Endnote 文献管理软件及 BibExcel 文献计量学分析软件,就微塑料与鱼类之间的几个主要方面进行概述,主要从鱼类受到微塑料污染现状、微塑料对鱼类产生毒性效应的相关要素(暴露方式、微塑料特征、鱼类的生理变化、受影响的器官和微塑料的归趋)、存在的问题与展望等进行了概述。

1　鱼类受到的微塑料污染现状(Contamination posed by MPs on fish)

本研究基于 Web of Science 中的核心合集数据库以布尔运算符"TS=Microplastic and TS=Fish"检索文献后将其导入 EndNote 软件中,利用 EndNote 智能分组功能筛选标题中含有"distribution"或"occurrence"或"present"或"ingest"或"uptake"不包含"shellfish"的文章,然后查找文章中研究区域的地理位置(坐标),将研究区域按国家、地区和海域归类统计研究频次。使用 ArcGIS 软件展示全球水生生态系统中鱼类受到微塑料污染情况及其被关注度(图 1)。

如图 1 所示,研究海洋鱼类最多的地区是地中海及其沿岸,其次是大西洋及其沿岸、里海及其沿岸、中国海域及近海岸。研究淡水生态系统中鱼类受到微塑料污染的主要地区是非洲、中国、美国和印度。在全球尺度上,鱼类受到的微塑料污染情况存在地域差异。与海洋环境相比,微塑料在淡水鱼类中的研究相对较少。而海洋中的大部分塑料都是先进入淡水环境后通过河流进入海洋,因此关于微塑料对淡水环境中鱼类影响的研究有待加强。就目前的研究情况来看,对淡水微塑料的研究主要集中在发达国家,在发展中国家的研究较少。由于在多数发展中国家的国内生产总值(GDP)中渔业占很大比重,这些国家的淡水河流受塑料污染最严重[18]。除受污染的分布区域外,受污染的个体比例与微塑料在鱼体内富集程度也是反映鱼类受污染情况的重要指标。由于环境中的微塑料污染存在动态变化,为展示不同研究区域的最新数据。将图 1 中各研究区域的相关文章按发表时间排序,选择近 5 年(2016—2020 年)调查数据,筛选出样本量 30 及以上的文章,以这些文章的数据分析相应区域鱼类受到的微塑料污染现状。表 1 汇总了不同区域鱼类体内检测到的微塑料的相关信息。如表 1 所示,不同研究区域鱼类受污染个体的比例(1.68% ~100%)存在一定差异,但所有调查区域的鱼类均受到不同程度的微塑料污染,其中,中国沿海的鱼类受到微塑料污染的个体比例(96.9% ~100%)比全球其他区域更高。之前

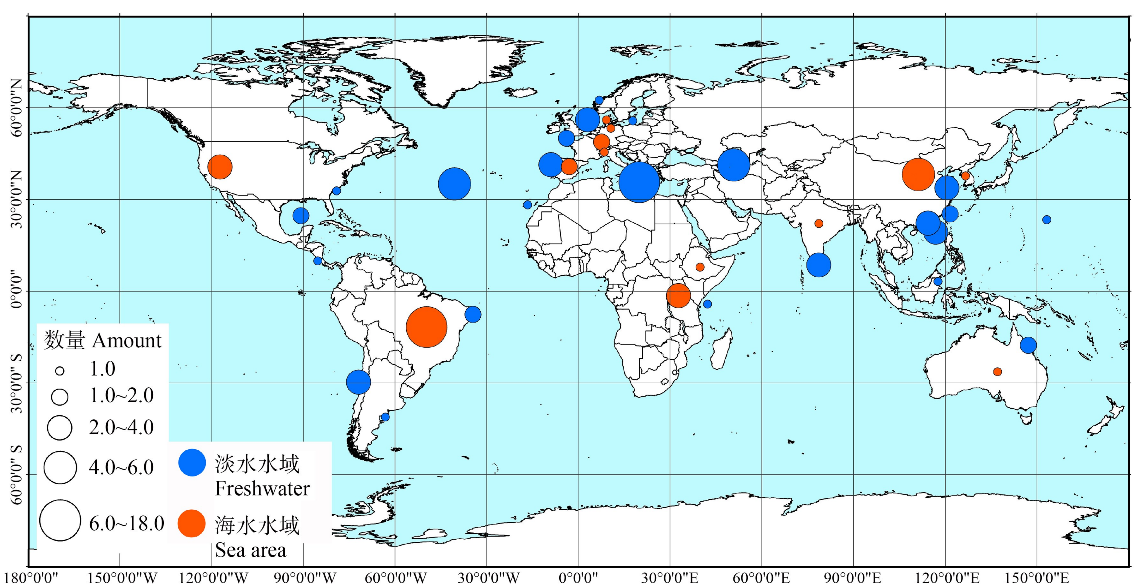

图 1　全球研究监测鱼类摄入微塑料的主要地区

Fig. 1　Major areas where fish ingesting microplastics (MP) were investigated all over the world

表1 全球不同地区鱼类体内检测到的微塑料特性

Table 1 Characteristics of MPs detected in fish samples from different locations

分类 Classification	区域 Region	个体数目 Number of sample	受污染个体比例/% Ratio of contaminated fish/%	微塑料含量/($items \cdot individual^{-1}$) MP concentration /($items \cdot individual^{-1}$)	检测到的微塑料特征 Characteristics of MPs detected				参考文献 Reference
					种类 Type	大小 Size	主要形状 Main shape	主要颜色 Main color	
淡水鱼种 Freshwater fish									
	中国三峡水库 Three Gorges Reservoir, China	35	25.7	0 ~ 3	PE, PA	0.3 ~ 1.8 mm	薄片 Sheet		[20]
	中国珠江 Pearl River, China	279	50	3 ~ 247	PE, PP, PE-PP, PET	>5 mm	纤维、碎片 Fiber and fragment	白色 White	[21]
	华东沿海河口 Coast and estuary area of East China	217	100	0.3 ~ 5.3	PET, PP, PE	>1 mm	纤维 Fiber		[22]
	印度维姆巴纳德湖 Vembanad Lake, India	123	26		PP, PET, PBT, 尼龙 (Nylon)	0.89 ~ 4.85 mm	碎片、泡沫、纤维 Fragments, foam and fibers	粉色、红色、黑色等 Pink, red, black, etc.	[23]
	坦桑尼亚维多利亚湖南岸 Southern shore of Victoria Lake, Tanzania	40	20		PE, PU, PET	<5 mm	碎片 Fragments	白色 White	[24]
	美国布拉索斯河流域 Brazos River Basin, USA	436	45			<5 mm	纤维 Fiber	灰色、蓝色 Gray, blue	[25]
	巴西欣古河 Xingu River, Brazil	172	26.7		PE, PVC, PA, PP	<5 mm	碎片 Fragments		[26]
	巴西帕鲁河 Pajeú River, Brazil	48	83	1 ~ 24		<5 mm	纤维 Fiber		[27]
	巴西铁特河与佩埃特河 Tietê River and Peixe River, Brazil	32	71.88	1.5 ~ 17.5		0.18 ~ 12.35 mm	纤维 Fiber	蓝色 Blue	[28]
海洋鱼种 Marine fish									
	中国南海 South China Sea	35	100	1 ~ 2.4		<5 mm	碎片 Fragments		[29]
	中国广东沿海 Estuarine areas of Guangdong, China	64	96.9	1.0 ~ 17.0		>1 mm	纤维 Fiber	白色 White	[30]
	印度东南沿海 Southeast coast of India	100	100	0.1 ~ 5.3	PE, PET, PA	0.5 ~ 5 mm	纤维 Fiber		[31]
	澳大利亚悉尼港 Sydney Harbor, Australia	93	43	0.2 ~ 4.6	PET		碎片 Fragments		[32]
	里海南部 Southern Caspian Sea	111	67.56	0.43 ~ 4.93		0.5 ~ 4.75 mm	纤维、碎片 Fiber, fragments	黑色 Black	[33]
	伊朗格罗根湾 Gorgan Bay, Iran	87	51.7	4 ~ 80	PP, PE, PA, PET	1 ~ 5 mm	纤维、碎片 Fiber, fragments	黑色、灰色 Black, gray	[34]
	地中海土耳其领海 Turkish territorial waters of the Mediterranean Sea	1 337	58	1 ~ 35	PS, IR	0.1 ~ 2.5 mm	纤维 Fiber		[35]

续表1

分类 Classification	区域 Region	个体数目 Number of sample	受污染个体比例/% Ratio of contaminated fish/%	微塑料含量/(items·individual^{-1}) MP concentration /(items·individual^{-1})	检测到的微塑料特征 Characteristics of MPs detected				参考文献 Reference
					种类 Type	大小 Size	主要形状 Main shape	主要颜色 Main color	
	地中海意大利领海 Italy territorial waters of the Mediterranean Sea	229	23.3	1 ~ 3		0.10 ~ 6.6 mm	纤维 Fiber		[36]
	地中海西部 Western Mediterranean Sea	125	16.8	0.25 ~ 4	PET, PEA		纤维 Fiber	透明 Transparent	[37]
	西班牙、法国、意大利和希腊沿海(地中海地区) Spain, France, Italy and Greece coastal areas of the Mediterranean Sea	884	46.8	1.6 ~ 14	PE, PP	0.6 ~ 1.8 mm	纤维 Fiber	黑色 Black	[38]
	西班牙巴利阿里群岛 Balearic Islands, Spain	337	68	2.47 ~ 4.89		1 nm ~ 5 mm	纤维 Fiber		[39]
	西班牙大西洋与地中海沿岸 Spanish Atlantic and Mediterranean coasts	212	17.5	0.6 ~ 3.2		0.38 ~ 3.1 mm	纤维 Fiber	黑色 Black	[40]
	葡萄牙蒙德古河 Mondego River, Portugal	120	38	1.4 ~ 14	PET, PP, PAN	<5 mm	纤维 Fiber	蓝色 Blue	[41]
	西英吉利海峡 Western English Channel	347	2.9		PA	50 ~ 1 100 μm	纤维 Fiber	蓝色 Blue	[42]
	北海与波罗的海 North Sea and Baltic Sea	290	5.5	0.2 ~ 0.8	PE	200 μm ~ 2.2 mm	碎片 Fragments		[43]
	南非沿海的德班港 Durban Harbour, South Africa	174	52	0.4 ~ 6	人造纤维 (Rayon), PET, 尼龙 (Nylon)	0.1 ~ 4.8 mm	纤维 Fiber	蓝色 Blue	[44]
	加纳海岸 Coast of Ghana	155	26 ~ 41	25.7 ~ 40		20.5 ~ 22.6 cm	小球、碎片 Pellets, fragments	白色、绿色 White, green	[45]
	巴西马曼瓜瓜河河口 Mamanguape River Estuary, Brazil	2 233	9	1 ~ 4			纤维 Fiber		[46]
	美国东海岸 East Coast of the United States	284	99	1.8 ~ 110		63 μm ~ 5 mm	纤维 Fiber		[47]
	加拿大纽芬兰岛沿岸 Island of Newfoundland, Canada	1 010	1.68			5 ~ 20 mm	纤维 Fiber	白色 White	[48]
	近哥斯达黎加的太平洋沿岸 Pacific coast of Costa Rica	30	100	32 ~ 42	PP, PE	0.1 ~ 2 mm	纤维 Fiber		[49]
	波利尼西亚莫雷阿岛 Moorea Island, French Polynesia	133	21	1 ~ 3		0.031 ~ 2.44 mm	碎片 Fragments		[50]
	北冰洋 Arctic Ocean	72	2.8			0.2 ~ 0.5 mm	纤维 Fiber		[51]

注:IR 表示异戊二烯;PA 表示聚酰胺;PAN 表示聚丙烯腈;PE 表示聚乙烯;PEA 表示聚丙烯酸酯;PP 表示聚丙烯;PE-PP 表示乙烯丙烯共聚物;PBT 表示聚对苯二酸丁二酯;PET 表示聚乙烯对苯二甲酸酯;PU 表示聚氨酯;PVC 表示聚氯乙烯;PS 表示聚苯乙烯。

Note: IR stands for isoprene; PA stands for polyamide; PAN stands for polyacrylonitrile; PE stands for polyethylene; PEA stands for polyacrylate; PP stands for polypropylene; PE-PP stands for ethylene propylene co-polymer; PBT stands for polybutylene terephthalate; PET stands for polyethylene terephthalate; PU stands for polyurethane; PVC stands for polyvinyl chloride; PS stands for polystyrene.

有文献综述也得到类似结果[19],该文献基于全球鱼类调查数据分析了鱼类受污染比例(图2)。在所有调查区域中,大部分地区50%及以上的鱼类受到微塑料污染,只有欧洲北部和一些深海海域的鱼类受污染较轻。如表1所示,不同区域鱼类个体检测到的微塑料的富集浓度范围为每个个体0~247个。其中,在中国珠江流域的罗非鱼肠道内检测到了高达每个个体247个的个体富集浓度。另外,鱼体内检测到最多的微塑料种类为聚乙烯(PE),最常见的微塑料形态为纤维状。

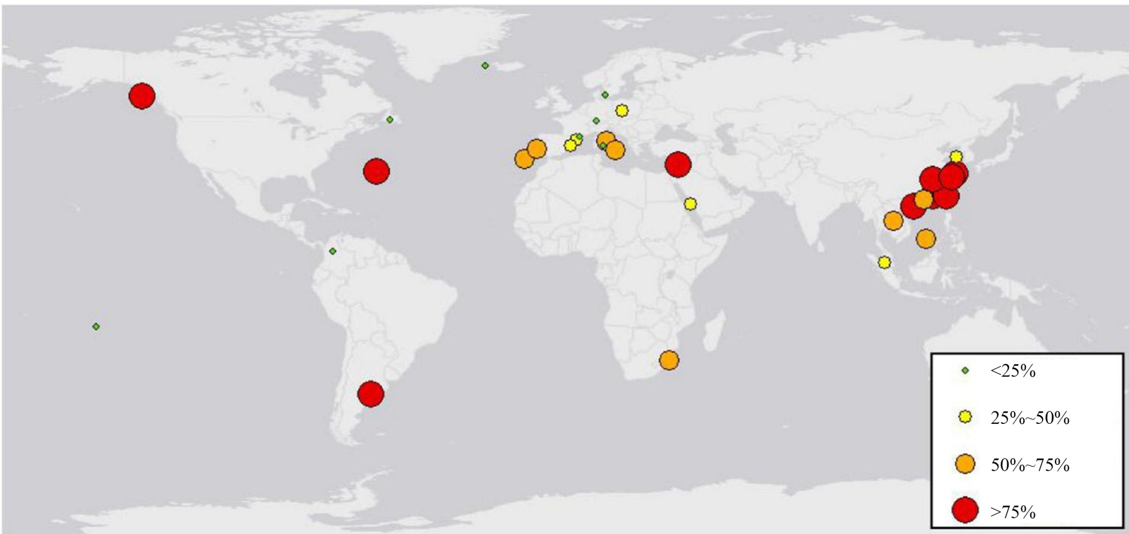

图2 体内含有微塑料的鱼的占比[19]

Fig. 2 Percentage of fish containing microplastics[19]

2 微塑料对鱼类产生的毒性效应的相关要素(Main elements of toxic effect of MPs on fish)

为全面分析微塑料对鱼类的影响,将以微塑料及鱼类为研究内容的检索结果导入BibExcel软件,利用共现词分析(Co-occurrence Analysis)功能找到在文献标题中出现的高频词汇,再根据暴露相关(暴露方式、发育阶段、微塑料参数)、效应相关(生理活动、组织器官)、归趋、研究目标(塑料种类、常用鱼类)进行分类整理,进一步统计相关词汇出现频次。最终得到微塑料对鱼类影响涉及的主要高频词汇及频次(图3)。本部分内容基于图3分析结果就微塑料对鱼类影响相关的几个主要方面(暴露方式、微塑料特征、生理活动、组织器官、微塑料归趋)进行了概述。

2.1 实验暴露方式

结合图3结果通过精读相关文献发现,与实验暴露方式相关的主要高频词汇为"rapid, chronic/long-term, single, combine"。根据暴露时间长短可以将暴露实验分为急性/短期暴露与慢性/长期暴露,根据暴露形式可以分为单一暴露与联合暴露。从暴露时间角度来看,不同暴露时间下微塑料对鱼类的毒性效应存在较大差别。之前,有综述论文汇总分析了一些以斑马鱼为研究对象的短期或中期暴露(最多42 d)试验结果,发现在效应类型和效应程度方面存在不同的结果[52]。作者通过概括分析发现,在出现毒性效应的研究中,急性暴露实验的主要特点是暴露时间短、污染物浓度较高、受试生物敏感,以幼鱼[53-54]居多;慢性或长期暴露实验的特点是暴露时间长、污染物浓度较低或接近环境浓度、受试生物敏感性低,以成鱼[55-57]为主。

除暴露时间上的差异外,不同研究采用的暴露形式也有较大差别。就单一暴露而言,通常选择人工合成的单一成分纯净微塑料,主要关注微塑料对鱼类的毒理学效应,如研究不同粒径微塑料对鱼的毒理学效应[58-59],较少关注其环境或生态毒性,且通常以高于环境浓度进行暴露。有研究者汇总了多项研究结果发现,在淡水环境(包括自然水体、自来水、瓶装水)中微塑料的浓度范围为 $1\times10^{-2}\sim1\times10^{8}$ 个·m^{-3},平均浓度为 5×10^{2} 个·m^{-3}[60]。而大部分单一暴露实验使用的浓度均高于该平均值(表2)。环境中的微塑料通常不是单一化合物,而是由聚合物和添加剂组成的混合物,这些聚合物和添加剂可以吸收

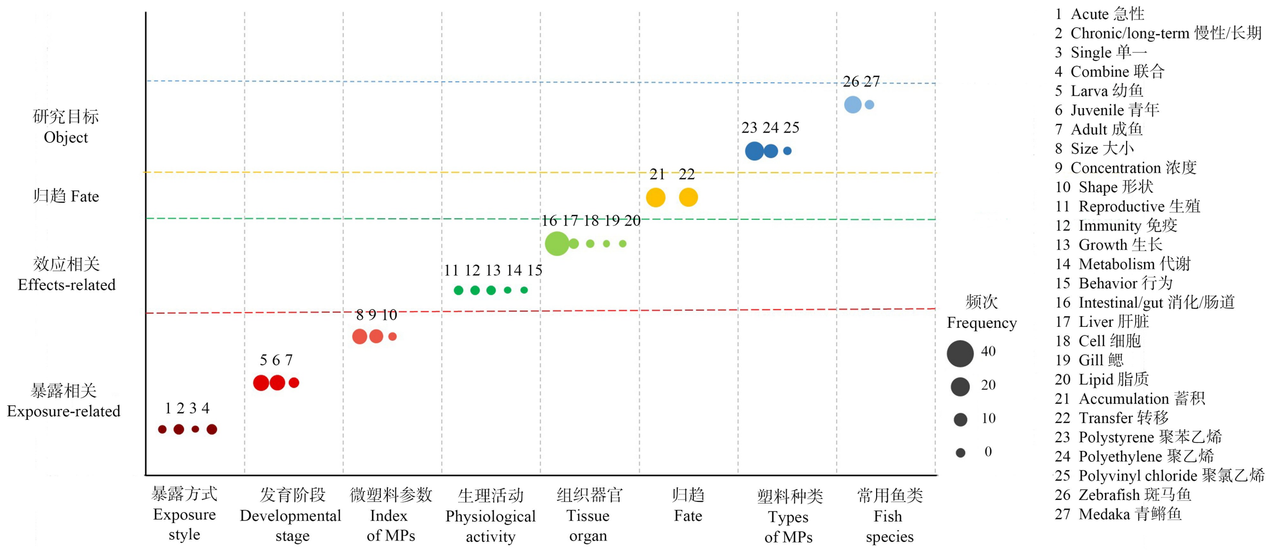

图 3　微塑料对鱼类影响涉及的主要高频词汇及频次(频次>5)

Fig. 3　High-frequency words (>5) appeared in the literatures on the influence of microplastics on fish

周围环境中的其他物质,包括有生命的物质、营养物质和污染物[61]等。因此,在研究微塑料对鱼类影响的研究中有一些实验是研究多种污染物联合暴露或塑料添加剂对鱼类的影响。联合暴露实验主要是关注微塑料及其吸附污染物的联合效应,其中包括微塑料与重金属(金[62]、镉[63]、银[64]、铅[65]和铜[66]等)或微塑料与有机污染物(多环芳烃[67]、卤代污染物[68]和芘[69]等)对鱼类的联合毒性。多数联合暴露实验结果显示联合暴露的毒性效应大于单一暴露[70-72]。但也有研究发现联合暴露下的毒性效应并未增强,Yan 等[65]以聚乙烯(PS)微塑料与重金属(镉、铅和锌)联合暴露海水青鳉(*Oryzias melastigma*),结果发现联合暴露并没有增加海水青鳉的生殖腺发育的风险。随着全球海洋塑料垃圾污染日益严重,增塑剂、阻燃剂等塑料添加剂对海洋动物的潜在影响也开始引起人们的关注[73]。早在十几年前,已有学者研究塑料添加剂对鱼类的影响。如 Cuq 等[74]研究了亲水性增塑剂对沙丁鱼(*Sardina pilchardus*)肌原纤维蛋白基膜功能特性的影响。

2.2　微塑料特征与毒性效应之间的关系

由于不同研究团队关注微塑料对鱼类毒性效应的研究目的不同,前期大量实验在使用微塑料暴露鱼类时使用的微塑料的相关参数(塑料种类、形状、大小、浓度等)也存在差异。本研究通过略读摘要筛选出微塑料对鱼类进行暴露的相关研究,通过精读文献的“材料与方法(material and methods)”汇总文献中涉及的鱼的种类、微塑料的特征(种类、形状、大小、浓度)数据及其关注的微塑料对鱼类产生的主要影响,结果见表 2。

如表 2 所示,受试生物中,淡水鱼类中的关于斑马鱼的研究最多,海洋鱼类中的海水青鳉研究较多。不同实验中所使用的微塑料种类、大小、形状、浓度存在一定差异。暴露实验中使用最多的是 PS,其次是 PE。大部分实验使用的微塑料是人工合成的单一成分的微塑料,只有少量实验使用塑料制品制作的微塑料或环境中收集的微塑料。由于受试生物、暴露浓度、暴露时间、研究目的的不同,上述微塑料特征与其对鱼类的影响之间尚无明确结论。就微塑料种类而言,有研究人员比较了不同种类微塑料(PS、PE 和 PET)对褐鳟(*Salmo trutta*)幼鱼的内分泌、遗传和细胞毒性的影响,发现不同聚合物对海鳟鱼幼鱼的遗传毒性大小顺序为:PS>PET>PE [115]。而另有研究认为微塑料对鱼的影响主要与微塑料浓度有关,与微塑料种类无关[117]。微塑料大小对鱼类的影响的研究结果也不尽相同,Yang 等[59]比较了纳米级(70 nm)与微米级(5 μm)PS 微塑料对鲫鱼(*Carassius auratus*)幼鱼的影响,他们发现高浓度的纳米微塑料和微米微塑料都可能对幼鱼造成损害,纳米微塑料潜在的危险性更大。而 Batel 等[118]的研究认为 4 ~ 6 μm 和 125 ~ 500 μm 的 PE 微塑料对鱼类产生的影响没有差异。除种类、大小外,还有研究人员比较了不同形状微塑料对鱼的影响,发现不规则形状

表 2 不同特征微塑料对鱼类主要影响汇总表

Table 2 Summary table of main influences of MPs with different characteristics on fish species

鱼种类 Fish species	微塑料特征 Characteristics of MPs				微塑料对鱼类产生的主要影响 Main effects on fish by MPs	参考文献 Reference
	塑料种类 Particle type	形状 Particle shape	大小 Particle size	浓度 Concentration		
多刺棘光鳃鲷 *Acanthochromis polyacanthus*	PET	颗粒 Pellets	2 mm	0.025, 0.055, 0.083, 0.1 $mg\cdot L^{-1}$	微塑料在消化道内滞留、生长抑制 Microplastics were trapped in intestine and growth inhibited	[75]
杜氏双边鱼 *Ambassis dussumieri*	原生塑料混合物 Mixture of virgin plastic	碎片、小球 Fragments, pellets	250 ~ 1 000 μm	0.1769 $mg\cdot L^{-1}$	生长缓慢、存活率下降 Growth slower and survival rate reduced	[76]
眼斑双锯鱼 *Amphiprion ocellaris*	PE	微球 Microspheres	180 ~ 212 μm	0.04, 0.2, 0.4, 2 $mg\cdot L^{-1}$	摄食行为变化 Ingestive behavior was changed	[77]
鲫鱼 *Carassius auratus*	PE	微球 Microspheres	100 ~ 500 μm	5%, 10%, 15%, 20%, 25% of diet	联合暴露下,鱼类对多氯联苯的同化效率降低 Assimilation efficiency of fish to polychlorinated biphenyls decreased under combined exposure	[71]
鲫鱼 *Carassius auratus*	PS	微球 Microspheres	70 nm, 5 μm	0.01, 0.1, 1 $mg\cdot L^{-1}$	氧化应激、多器官损伤、生长抑制 Oxidative stress, multiple organ injury and growth inhibited	[59]
鲫鱼 *Carassius auratus*	Mixture	微纤维、微珠 Microfibers, microplastic beads	Fibers (50, 500 μm), beads (200 μm)	50 microbeads or 50 microfibers per diet	微塑料在消化道内滞留 Microplastics were trapped in the intestine	[78]
尖齿胡鲶 *Clarias gariepinus*	PVC	粉末 Powdered form	(95.41 ± 4.23) μm	diets at 0.5, 1.5, 3.0 percentage	氧化应激、肝脏损伤 Oxidative stress and liver injury	[79]
尖齿胡鲶 *Clarias gariepinus*	PVC	碎片 Fragments	(95.41 ± 4.23) μm	0.50%, 1.50%, 3.0% of diet	神经毒性、氧化应激 Neurotoxic and oxidative stress	[80]
突唇白鲑 *Coregonus lavaretus*	PS	微球 Microspheres	90 mm	7.5, 30 $particles\cdot mL^{-1}$	子代未获得遗传适应性 Larval fish don't have genetic adaptation	[81]
鲤鱼 *Cyprinus carpio*	洗面奶或护体乳中的微塑料 Be isolated from one of the most popular brands of a face and body scrub	微球 Microspheres		0.25 $mg\cdot L^{-1}$	内分泌干扰、免疫反应 Endocrine disruption and immune response	[82]
鲤鱼 *Cyprinus carpio*	PVC	微球 Microspheres	100 ~ 200 μm	0.00555, 0.0911, 0.13665 $mg\cdot L^{-1}$	生长抑制、氧化应激 Growth inhibited and oxidative stress	[83]

续表2

鱼种类 Fish species	微塑料特征 Characteristics of MPs				微塑料对鱼类产生的主要影响 Main effects on fish by MPs	参考文献 Reference
	塑料种类 Particle type	形状 Particle shape	大小 Particle size	浓度 Concentration		
杂色鳉 *Cyprinodon variegatus*	PE	不规则形状或球形 Irregularly shaped and spherical	150 ~ 180 μm, 6 ~ 350 μm	50, 250 $mg \cdot L^{-1}$	消化道活性氧含量增加 Reactive oxygen in digestive tract was increased	[84]
斑马鱼 *Danio rerio*	PE	微球 Microspheres	1 ~ 5,10 ~ 20 μm	2.52 $mg \cdot L^{-1}$	胚胎毒性 Embryotoxicity	[57]
斑马鱼 *Danio rerio*	PE	微球 Microspheres	1 ~ 5 μm, 120 ~ 220 μm	2% of food	无病理学损伤 No histopathological changes occurred	[85]
斑马鱼 *Danio rerio*	PE	碎片 Fragments	10 ~ 45 μm	20 $mg \cdot L^{-1}$	炎症反应 Inflammatory response	[86]
斑马鱼 *Danio rerio*	PE	碎片 Fragments	10 ~ 22, 45 ~ 53, 90 ~ 106, 212 ~ 250, 500 ~ 600 μm	2 $mg \cdot L^{-1}$	游泳行为异常、神经毒性 Swimming behavior changed, neurotoxicity	[87]
斑马鱼 *Danio rerio*	PE	微球 Microspheres	10 ~ 106 μm	10, 100, 1 000 $particles \cdot mL^{-1}$	降低鱼体内金属污染物的吸收利用率 Absorption and utilization rate of metal pollutants in fish decreased	[64]
斑马鱼 *Danio rerio*	PE	微球 Microspheres	250 ~ 300 μm	25, 50 $mg \cdot L^{-1}$	摄食行为变化 Ingestive behavior was changed	[88]
斑马鱼 *Danio rerio*	PE	碎片 Fragments	10 ~ 45 μm	20 $mg \cdot L^{-1}$	发育毒性 Development toxicity	[89]
斑马鱼 *Danio rerio*	PE	微球 Microspheres	11 ~ 13 μm	10, 100 $mg \cdot L^{-1}$	胚胎毒性 Embryotoxicity	[90]
斑马鱼 *Danio rerio*	PE, PET, PVC	碎片 Fragments	200 μm	0, 125, 250, 500 $mg \cdot L^{-1}$	改变微塑料中释放出的铅的生物有效性 Bioavailability of lead released from microplastics was changed	[91]
斑马鱼 *Danio rerio*	PS	微球 Microspheres	70 nm	0.5, 1.5, 5 $mg \cdot L^{-1}$	神经损伤、生殖毒性、氧化损伤 Nerve damage, reproductive toxicity and oxidative damage	[92]
斑马鱼 *Danio rerio*	PS	微球 Microspheres	70 nm, 5 μm, 20 μm	0.02, 0.2, 2 $mg \cdot L^{-1}$	氧化应激、肝脏代谢变化 Oxidative stress and liver metabolism was changed	[93]

续表2

鱼种类 Fish species	微塑料特征 Characteristics of MPs 塑料种类 Particle type	形状 Particle shape	大小 Particle size	浓度 Concentration	微塑料对鱼类产生的主要影响 Main effects on fish by MPs	参考文献 Reference
斑马鱼 *Danio rerio*	PS	微球 Microspheres	1 μm	0.01, 0.1, 1 mg·L^{-1}	遗传毒性 Genetic toxicity	[94]
斑马鱼 *Danio rerio*	PS	微球 Microspheres	50, 500 nm	0.1, 1, 10 mg·L^{-1}	尾鳍再生能力下降 Caudal fin regeneration was inhibited	[95]
斑马鱼 *Danio rerio*	PS	微球 Microspheres	0.5, 50 μm	0.1, 1 mg·L^{-1}	改变肠道微生物组成、肠道发生炎症反应 Intestinal microbial composition was changed, intestinal inflammation	[56]
斑马鱼 *Danio rerio*	PS	微球 Microspheres	5 μm	0.001 ~ 20 mg·L^{-1}	改变游泳行为 Swimming behavior was changed	[96]
斑马鱼 *Danio rerio*	PS	纤维、碎片、珠子 Fibers , fragments, beads	Fibers (25 μm), fragments (<10 μm), beads (15 μm)	20 mg·L^{-1}	消化道损伤、影响肠道微生物 Intestinal lesions and influenced the gut microbiota	[97]
斑马鱼 *Danio rerio*	PS	微球 Microspheres	0.1 μm, 20 μm	0.2 mg·L^{-1}	增加铜离子在肝脏、肠道内蓄积、氧化应激 Accumulation of copper ions in the liver and intestines was increased, oxidative stress	[70]
欧洲舌齿鲈 *Dicentrarchus labrax*	PE	粉末 Powders	125 ~ 250 μm	食物质量的2% 2% of food mass	影响肝脏代谢、氧化应激、免疫反应 Liver metabolism affected, oxidative stress and innate immune response	[68]
欧洲舌齿鲈 *Dicentrarchus labrax*	PE	微球 Microspheres	10 ~ 45 μm	10 ~ 100 microbeads ·mg^{-1} (diet)	死亡率升高、生长减缓、炎症反应 Mortality increased, growth slower and inflammation	[98]
欧洲舌齿鲈 *Dicentrarchus labrax*	PE, PVC	粉末 Powders	40 ~ 150 μm	10^3, 10^4, 10^5 mg·L^{-1}	先天免疫反应、炎症、氧化应激 Innate immune response, inflammation and oxidative stress	[99]
欧洲舌齿鲈 *Dicentrarchus labrax*	PS	微球 Microspheres	1 ~ 5 μm	0.26, 0.69 mg·L^{-1}	游泳行为改变 Swimming behavior was changed	[72]
白鲷 *Diplodus sargus*	PS	碎片 Fragments,	500 ~ 1 000 μm	4 241 particles·m^{-3}	摄食行为变化 Ingestive behavior was changed	[53]
云纹石斑鱼 *Epinephelus moara*	PS	微球 Microbeads	20 ~ 100 μm	2.0, 20 mg·g^{-1} (dry feed)	肝脏脂质代谢紊乱 Liver lipid metabolism was disturbed	[100]

续表2

鱼种类 Fish species	微塑料特征 Characteristics of MPs 塑料种类 Particle type	形状 Particle shape	大小 Particle size	浓度 Concentration	微塑料对鱼类产生的主要影响 Main effects on fish by MPs	参考文献 Reference
三刺鱼 *Gasterosteus aculeatus*	PE	微珠、微纤维 Microbeads, microfibers	Microbeads (27 ~ 32 μm), microfibers (500 μm)	100 000 particles·L^{-1}	微塑料在肠道、鳃中滞留 Microplastics were retained in fish intestine and gill	[101]
光鲵 *Girella laevifrons*	PS	微球 Microspheres	8 μm	0.001, 0.01 g·d^{-1}	肠道损伤 Intestinal lesions	[102]
尖吻鲈 *Lates calcarifer*	PS	碎片 Fragments	97 μm	100 particles·L^{-1}	摄食行为变化 Ingestive behavior was changed	[103]
泥鳅 *Misgurnus anguillicaudatus*	PVC		< 10 μm	50 mg·L^{-1}	肝脏损伤 Liver injury	[104]
虹鳟 *Oncorhynchus mykiss*	PE	微球 Microspheres	10 ~ 106 μm	1 000 particles·mL^{-1}	微塑料增加可吸附污染物进入鱼体内的风险 Risk of contaminants absorbed into fish was increased	[105]
虹鳟 *Oncorhynchus mykiss*	PS	粉末 Powders	100 ~ 400 μm	500 ~ 700, 2 226 ~ 2 411 particles·$fish^{-1}$·d^{-1}	肝脏损伤、影响脂质代谢 Liver injury and lipid metabolism was affected	[106]
虹鳟 *Oncorhynchus mykiss*	PS	微珠 Microbeads	220 nm	50 mg·L^{-1}	细胞毒性、基因毒性 Cytotoxicity and genotoxicity	[67]
罗非鱼 *Oreochromis niloticus*	PS	珠子 Beads	0.3, 5, 70 ~ 90 μm	0.1 mg·L^{-1}	神经毒性、氧化应激、影响肝脏代谢 Neurotoxicity, oxidative stress, and liver metabolism was affected	[58]
日本青鳉 *Oryzias latipes*	环境微塑料 Environmental microplastics		0.1 ~ 1 000 μm	0.01%, 0.1%, 1% (*m/m*) in fish food	发育毒性、存活率下降、行为变化 Development toxicity, survival rate declined and behavior was changed	[107]
日本青鳉 *Oryzias latipes*	PE, PP	线状 Thread	PE (10 ~ 20 μm), PP (50 ~ 60 μm)	1 000, 10 000 fibers·L^{-1}	产卵率升高、鳃损伤 Increased spawning rate, gill injury	[55]
日本青鳉 *Oryzias latipes*	PE	微球 Pellets	3 mm	0.008 mg·L^{-1}	内分泌干扰 Endocrine disruption	[108]
海水青鳉 *Oryzias melastigma*	PS	微球 Microspheres	10 μm	100 000 particles·L^{-1}	误食 Ingested by mistake	[109]
海水青鳉 *Oryzias melastigma*	PS	微球 Microspheres	0.05, 0.50, 6.00 μm	0.1, 1×10^3, 1×10^6 particles·mL^{-1}	发育毒性 Development toxicity	[110]

续表2

鱼种类 Fish species	微塑料特征 Characteristics of MPs				微塑料对鱼类产生的主要影响 Main effects on fish by MPs	参考文献 Reference
	塑料种类 Particle type	形状 Particle shape	大小 Particle size	浓度 Concentration		
海水青鳉 *Oryzias melastigma*	PS	微球 Microspheres	10 μm	0.002, 0.02, 0.2 $mg \cdot L^{-1}$	生殖毒性 Reproductive toxicity	[111]
海水青鳉 *Oryzias melastigma*	PS	微球 Microspheres	2.5 μm	0.1 $mg \cdot L^{-1}$	影响肠道微生物、影响性腺发育 Perturb gut microbiota homeostasis and gonadal development	[65]
黑头软口鲦 *Pimephales promelas*	PE	微球 Microspheres	180～212 μm	250～500 $particles \cdot L^{-1}$	摄食行为改变、影响生长 Impact the foraging and growth	[112]
黑头软口鲦 *Pimephales promelas*	PC, PS		PS (41.0 nm), PC (158.7 nm)	0.1 $mg \cdot L^{-1}$ plasma	先天免疫反应 Innate immune response	[113]
黑头软口鲦 *Pimephales promelas*	轮胎橡胶颗粒 Tire crumb rubber	碎片 Fragments	38～355 μm	300, 1 900, 6 000 $mg \cdot L^{-1}$	被摄食并在消化道内积累 Ingested and accumulated in the intestinal tract	[114]
小眼长臀鰕虎 *Pomatoschistus microps*	PE	微球 Microspheres	1～5 μm	0, 0.0184, 0.184 $mg \cdot L^{-1}$	增加可吸附芘对小眼长臀鰕虎的毒性 Have greater effect than the pyrene alone on *Pomatoschistus microps*	[69]
条纹鲮脂鲤 *Prochilodus lineatus*	PE	微球 Microspheres	10～90 μm	0.02 $mg \cdot L^{-1}$	增加可吸附铜离子对条纹鲮脂鲤的毒性 Have greater effect than the copper alone on *Prochilodus lineatus*	[66]
褐鳟 *Salmo trutta*	PE, PET, PS	微球 Pellets	3 000 μm	2.8 $mg \cdot L^{-1}$	遗传毒性 Genetic toxicity	[115]
紫青鰤鲳 *Seriolella violacea*	人工合成微塑料 Artificial microplastics	管状 Tubular	长度 Length (1.2±0.2) mm, 直径 Diameter (1.0±0.1) mm	1∶6 (*m*/*m*) in fish food	优先摄食类似于食物颗粒的黑色微塑料 Capture preferentially black microplastics, which is similar to food pellets	[116]
金头鲷 *Sparus aurata*	PA, PE, PS, PVC	球形 Spherical pellets	<2 mm	0.1 $g \cdot kg^{-1} \cdot d^{-1}$	无影响 No imminent harm	[117]
金头鲷 *Sparus aurata*	PE, PVC	粉末 Powders	40～150 μm	10^3, 10^4, 10^5 $mg \cdot L^{-1}$	先天免疫反应、炎症反应、氧化应激 Innate immune response, inflammation and oxidative stress	[99]
黄棕盘丽鱼 *Symphysodon aequifasciatus*	PS	微球 Microspheres	32～40 μm	0, 0.05, 0.5 $mg \cdot L^{-1}$	抗氧化防御和先天免疫反应 Antioxidant defense and innate immune response	[63]

注：PA 表示尼龙，PC 表示聚碳酸酯，PE 表示聚乙烯，PET 表示聚对苯二甲酸乙二酯，PS 表示聚苯乙烯，PVC 表示聚氯乙烯，PP 表示聚丙烯。

Note: PA stands for polyamide; PC stands for polycarbonate; PE stands for polyethylene; PET stands for polyethylene terephthalate; PS stands for polystyrene; PVC stands for polyvinyl chloride; PP stands for polypropylene.

PE 微塑料对鱼类游泳行为影响较球形微塑料更明显[84]。而 Qiao 等[97]研究不同形状 PS 微塑料(纤维、碎片和圆球)对斑马鱼的影响时发现纤维微塑料导致的肠道毒性大于碎片微塑料和球形微塑料。微塑料的暴露浓度也是影响其被鱼类摄入的重要因素之一。通常认为鱼类摄入微塑料的量与微塑料浓度成正比,但 Mbedzi 等[119]开发并应用了一种功能响应方法,以量化鱼类对不同浓度的微塑料的摄取情况,发现斯氏罗非鱼(*Tilapia sparrmanii*)在环境浓度相对较低的情况下依然会摄取 PE 微塑料,当浓度升高时,摄取量增加但不具有统计显著性。综上,微塑料的各特征参数与其对鱼类产生的毒性效应都存在一定关系,但由于缺乏多物种、多微塑料参数的综合实验,当前阶段的研究结果尚无关于微塑料特征与其对鱼类产生的毒性效应关系的明确结论。

2.3　鱼类受微塑料影响的生理活动

根据标题共现词分析结果(图 3),目前微塑料对鱼类生理活动的影响主要涉及生殖、免疫、生长、代谢、行为等方面。之前,有文章综述了微塑料对水生生物(贝壳类、鱼类等)的生殖影响,发现微塑料暴露对水生生物生殖的影响因物种而异,但多数研究结果表明,微塑料暴露后水生生物的生殖细胞和卵母细胞质量、繁殖能力、精子游动速度和后代质量等显著降低[120]。其中,关于鱼类的研究中,主要关注微塑料对鱼类性腺的影响。其中有微塑料对性腺的直接作用,Sarasamma 等[92]以纳米微塑料暴露斑马鱼发现纳米微塑料会在斑马鱼性腺中积累;也有微塑料对性腺的间接作用,Wang 等[111]以不同浓度的 10 μm PS 微塑料暴露海水青鳉,发现微塑料可以影响下丘脑-垂体-性腺轴,延缓了雌性海水青鳉鱼性腺的成熟。

微塑料对鱼类免疫的影响主要是从基因、酶或蛋白、细胞水平开展研究。在基因水平上,微塑料主要影响鱼类炎症反应及细胞免疫的相关基因的表达。Chen 等[110]以 PS 微塑料暴露海水青鳉,发现参与炎症反应及免疫相关的基因:络氨酸激酶(Janus kinase)、趋化因子配体 11 (C-C motif chemokine 11)、白细胞介素 6 (interleukin 6)表达均发生显著变化。在酶或蛋白水平上,微塑料主要影响鱼类免疫蛋白及与免疫调节相关的酶的变化。Banaee 等[82]以微塑料与镉联合暴露鲤鱼(*Cyprinus carpio*),发现联合暴露下鲤鱼的总免疫球蛋白水平发生显著变化。但 Espinosa 等[121]以 PVC 微塑料通过食物相暴露金头鲷发现 PVC 微塑料对金头鲷的免疫球蛋白水平影响不大。在细胞水平上,研究人员主要关注微塑料对免疫细胞的影响。Greven 等[113]以 PS、PC 的微米级与纳米级塑料暴露黑头软口鲦(*Pimephales promelas*)后发现中性粒细胞吞噬 PS 纳米颗粒,他们推测这将影响黑头软口鲦的免疫响应。

鱼类生长相关的直接生理指标是体质量、体长变化。关于微塑料对鱼类生长影响的研究结论主要是生长抑制,但抑制程度不同。Naidoo 和 Glassom[76]在环境中收集经微塑料长期暴露(95 d)后的金鱼,发现暴露组中金鱼的体质量、体长增加量较对照组都有所下降。Xia 等[83]研究了不同浓度、不同暴露时间下,PVC 微塑料对鲤鱼(*Cyprinus carpio* var.)的影响,发现随浓度增加,鲤鱼体质量增加量降低,对体长影响不明显。而 Cedervall 等[122]研究纳米 PS 微塑料经三级食物链传递后对鲫鱼(*Carassius carassius*)的影响,发现鲫鱼体质量下降。上述研究认为微塑料暴露后体质量增长变慢的可能原因有:微塑料暴露引起鱼类的消化道堵塞或消化道损伤或发生炎症反应,影响食物摄入和消化道对营养物质的吸收;引起肝脏损伤,影响鱼类肝脏的脂质代谢功能,进而导致体质量增加变慢。也有一些研究发现微塑料对鱼类生长影响不明显。Critchell 和 Hoogenboom[75]研究 PET 微塑料对多刺棘光鳃鲷(*Acanthochromis polyacanthus*)的影响,发现暴露组与对照组相比,鱼的体质量、体长变化均无差异。研究人员推测出现上述结果的原因是:鱼类可将微塑料排出体外,从而减小微塑料对消化道的损伤;鱼类对微塑料有一定识别能力,可以避免误食。

通过汇总分析发现,研究鱼类代谢的相关文献主要是关注鱼类的脂类、能量代谢。目前,研究微塑料对鱼类代谢影响的方法之一是利用代谢组学技术研究代谢物的变化。Zhao 等[123]从代谢组学角度研究发现丁基羟基苯甲醚和微塑料联合暴露下斑马鱼幼鱼发育异常的原因是 2 种物质干扰了花生四烯酸、甘油磷脂和脂类的代谢。还有研究人员关注代谢过程中一些蛋白和酶的变化。Cedervall 等[122]研究了纳米微塑料经三级食物链传递后对鲫鱼(*Carassius carassius*)影响,发现鲫鱼的脂肪代谢发生变化,其主要原因是纳米颗粒结合了血清中的载脂蛋白(apolipoprotein A ~ I),抑制载脂蛋白利用体内储备的脂肪。Wen 等[124]对比了微塑料与温度变化对黄棕盘丽鱼(*Symphysodon aequifasciatus*)代谢的影响,

发现微塑料对能量代谢相关的酶(乙酰胆碱酯酶、碱性磷酸酶乳酸脱氢酶、柠檬酸合酶和细胞色素 c 氧化酶)的活性有影响,干扰了鱼的能量代谢。

鱼类的行为变化也是研究环境毒物对鱼类影响的重要指标。研究微塑料对鱼类行为影响的文献中涉及的主要行为包括游泳行为、摄食行为、攻击性等。目前,微塑料暴露后鱼类的游泳行为变化尚无一致结论。Barboza 等[72]研究了微塑料与汞对欧洲舌齿鲈鱼的联合毒性,发现在单一或联合暴露下欧洲鲈鱼的游泳速度均下降。而 Chen 等[96]以多种浓度的 PS 微塑料暴露斑马鱼成鱼,发现微塑料暴露后斑马鱼变得极度活跃,其游泳距离比对照组增加了 1.3 倍~2.4 倍。微塑料对鱼类摄食方面影响的研究主要集中在摄食量与微塑料浓度的关系[119]及鱼类是否可以辨识微塑料。通常的暴露实验认为鱼类不能辨识微塑料,但也有学者发现鱼类可以辨识微塑料。Kim 等[88]发现斑马鱼在摄入 PE 微塑料(247.5 μm)后表现出喷吐行为,说明斑马鱼对微塑料有一定的识别能力。McCormick 等[125]在研究野外环境中微塑料对革狗母鱼(*Synodus dermatogenys*)的行为影响时也得到相似的结果。也有研究认为微塑料暴露不会影响鱼类的行为。Critchell 和 Hoogenboom[75]在研究 PET 微塑料对一种岩礁鱼的影响时发现微塑料对其游泳、摄食及攻击性均没有影响。

通过分析鱼类受到微塑料影响的生理活动的相关内容,发现在细胞或分子水平上产生这些毒性效应的机制主要包括:氧化应激、炎症反应、免疫细胞应答、脂质过氧化、DNA 断裂、细胞膜稳定性变化、细胞坏死、代谢或解毒相关通路的激活等。

2.4 鱼体中受微塑料影响的器官

从器官角度分析,大部分研究关注微塑料对鱼类的肝脏和消化道(肠道微生物)及鳃的影响。肝脏是鱼类脂质代谢的主要器官,脂质代谢是鱼类的主要能量来源[126],所以研究人员关注微塑料对鱼类肝脏脂质代谢功能的影响。且多数研究发现微塑料暴露会造成肝脏损伤[70]、氧化应激[93]或影响肝脏的代谢功能,特别是脂质代谢[100]等。消化道作为鱼类摄入微塑料后微塑料存在的主要器官,其是否受到微塑料影响也是很多学者关注的问题之一。微塑料对鱼类消化道的最直接影响肠道损伤[97, 127],有研究发现不同部位损伤程度不同,与肠道前端、中部相比,末端肠道损伤最严重[127]。其次是影响消化道对营养物质[76]或有毒物质(如铜[66]、银[105])的吸收,多项研究发现微塑料存在降低了鱼肠道对重金属的吸收。有学者认为肠道微生物是生物体的“特殊器官”[128],与生物体的健康息息相关,因此也有学者关注微塑料对鱼肠道微生物的影响。目前研究认为微塑料对鱼类肠道微生物的影响主要是影响其肠道微生物组成[129]、多样性和丰度[65]及功能[130]。微塑料的密度与水接近,因此会悬浮在水中,鳃作为鱼类呼吸和废物交换的关键部位[131],在鱼类呼吸的同时会过滤水中的悬浮物,所以鳃也是鱼类直接接触微塑料的主要器官之一。已有研究证实野外环境中捕获的鱼的鳃丝中有微塑料存在[132],这可能会影响鳃发挥其正常功能。另外,在实验室暴露实验中也发现微塑料会在鳃中大量积累[57]。

2.5 鱼体内微塑料的归趋

由于微塑料具有持久性、难降解等特点,进入鱼体内的微塑料很可能在鱼体内富集。之前有基于文献计量学分析的综述文章认为,未来的研究应重点关注微塑料在食物链中的迁移、积累和影响[133]。因此,明确鱼体内微塑料的归趋对研究其毒性效应、生物富集和食物链传递都具有重要意义。目前,鱼体内微塑料的归趋途径主要包括:排泄、器官间转移和食物链传递。有暴露实验在鱼排出的粪便中检测到了微塑料[134],说明微塑料有重新进入环境造成二次污染或持久污染的潜在风险。另有研究人员关注微塑料在鱼体内的转移,即进入鱼体内的微塑料从消化道进入鱼的其他组织器官,发现 5 μm 的 PS 微塑料可以进入斑马鱼的肝脏[93]。这说明粒径在 5 μm 以下的微塑料可以从消化道进入其他内脏器官。研究人员还关注了微塑料在食物链中的传递。Cedervall 等[122]发现纳米级 PS 微塑料颗粒可以通过捕食关系从藻类转移到浮游动物再转移到鱼类体内。Zhang 等[135]研究了微塑料在中国东海野生鱼类和甲壳类动物之间的食物网转移,发现微塑料很可能在海洋食物网的高营养级鱼类中富集。由于微塑料既能在鱼体内富集,又可以沿食物链传递,加之其对生命体存在一定的毒性效应,微塑料最终可能通过食物链传递威胁人类健康。

3 存在的问题与展望(Problems and prospective)

首先,通过文献计量学分析发现,与海洋鱼类相比微塑料在淡水鱼类中的调查数据相对较少。而海洋中的大部分塑料都是先进入淡水环境后通过河流进入海洋,因此关于微塑料对淡水环境中鱼类污染

情况的研究有待加强。前期野外调查研究的检测方法参差不齐,后续对环境中的微塑料的检测时需要规范统一的环境分析方法。第二,目前的统计结果显示,无论急性暴露还是长期暴露实验所使用的微塑料浓度多高于环境水体中的浓度。早在 2016 年就有研究人员提出,微塑料暴露研究应该符合环境实际[136]。以后关于微塑料的毒理学研究中如果只研究微塑料的毒性效应可以以高于环境的浓度进行暴露实验,但是如果是研究微塑料对鱼类的生态效应时必须以环境浓度为参考。而且除环境水体中检测到的浓度外,野外捕获鱼类体内检测到的浓度也具有重要参考价值。第三,由于微塑料形状、大小、密度存在差异,颗粒浓度与质量浓度之间无法换算,因此以后的研究中应采用统一的浓度单位,以便对不同研究结果进行比较分析。而且需要将毒性测试方法标准化,尤其是如何配制稳定的实验溶液。如果出现沉淀或团聚,则实验周期内的测量浓度会随时间降低。已有的多数暴露实验使用球形塑料,而实际环境中微塑料形状不规则。因此在以后的暴露实验中可考虑使用野外收集的微塑料进行暴露,以更好地模拟实际环境中的微塑料污染风险。但使用原生微塑料进行试验时如何避免微塑料毒性测试中塑料添加剂溶出产生的影响也是目前科研人员必须考虑的一个重要问题。第四,研究认为微塑料可以通过排泄重新进入环境,目前缺乏关于排泄物中的微塑料是否继续影响环境中生物的研究。加强相关研究可以更好地了解微塑料的环境行为。另外,加强对野外鱼类体内的微塑料污染情况监测对生态系统健康具有重要意义,特别是利用鱼类受污染的数据进行生态风险评估[137]。

通讯作者简介:黄乾生(1982—),男,博士,副研究员,主要研究方向为环境毒理学、生态毒理学、有机污染物的健康效应、环境有机污染物的健康风险及其机制等。

共同通讯作者简介:董四君(1966—),男,博士,研究员,主要研究方向为环境毒理学、生态毒理学、环境防卫医学和肠道微生态学等。

参考文献(References):

[1] Koelmans A A, Besseling E, Wegner A, et al. Plastic as a carrier of POPs to aquatic organisms: A model analysis [J]. Environmental Science & Technology, 2013, 47(14): 7812-7820

[2] Andrady A L. Microplastics in the marine environment [J]. Marine Pollution Bulletin, 2011, 62(8): 1596-1605

[3] Thompson R C, Olsen Y, Mitchell R P, et al. Lost at sea: Where is all the plastic? [J]. Science, 2004, 304(5672): 838

[4] Sarijan S, Azman S, Said M I M, et al. Microplastics in freshwater ecosystems: A recent review of occurrence, analysis, potential impacts, and research needs [J]. Environmental Science and Pollution Research International, 2021, 28(2): 1341-1356

[5] Li C R, Busquets R, Campos L C. Assessment of microplastics in freshwater systems: A review [J]. Science of the Total Environment, 2020, 707: 135578

[6] Mishra S, Rath C C, Das A P. Marine microfiber pollution: A review on present status and future challenges [J]. Marine Pollution Bulletin, 2019, 140: 188-197

[7] Ribeiro-Brasil D R G, Torres N R, Picanço A B, et al. Contamination of stream fish by plastic waste in the Brazilian Amazon [J]. Environmental Pollution, 2020, 266: 115241

[8] Qin F, Du J, Gao J, et al. Bibliometric profile of global microplastics research from 2004 to 2019 [J]. International Journal of Environmental Research and Public Health, 2020, 17(16): 5639

[9] 孙康, 周晓静, 苏子晓, 等. 中国海洋渔业资源可持续利用的动态评价与空间分异[J]. 地理科学, 2016, 36(8): 1172-1179

Sun K, Zhou X J, Su Z X, et al. Dynamic assessment and spatial differentiation of sustainable utilization of marine fishery resources in China [J]. Scientia Geographica Sinica, 2016, 36(8): 1172-1179 (in Chinese)

[10] 丁琪, 陈新军, 李纲, 等. 基于渔获统计的西北太平洋渔业资源可持续利用评价[J]. 资源科学, 2013, 35(10): 2032-2040

Ding Q, Chen X J, Li G, et al. Catch statistics and the sustainable utilization of northwest Pacific Ocean fishery resources [J]. Resources Science, 2013, 35(10): 2032-2040 (in Chinese)

[11] Bhathal B, Pauly D. 'Fishing down marine food webs' and spatial expansion of coastal fisheries in India, 1950—2000 [J]. Fisheries Research, 2008, 91(1): 26-34

[12] Freire K M F, Pauly D. Fishing down Brazilian marine food webs, with emphasis on the east Brazil large marine ecosystem [J]. Fisheries Research, 2010, 105(1): 57-62

[13] Elizalde-Velázquez A, Carcano A M, Crago J, et al. Translocation, trophic transfer, accumulation and depuration of polystyrene microplastics in *Daphnia magna* and *Pimephales promelas* [J]. Environmental Pollution, 2020,

259: 113937

[14] Li W C, Tse H F, Fok L. Plastic waste in the marine environment: A review of sources, occurrence and effects [J]. Science of the Total Environment, 2016, 566-567: 333-349

[15] Ajith N, Arumugam S, Parthasarathy S, et al. Global distribution of microplastics and its impact on marine environment: A review [J]. Environmental Science and Pollution Research International, 2020, 27(21): 25970-25986

[16] Markic A, Gaertner J C, Gaertner-Mazouni N, et al. Plastic ingestion by marine fish in the wild [J]. Critical Reviews in Environmental Science and Technology, 2020, 50 (7): 657-697

[17] Collard F, Gasperi J, Gabrielsen G W, et al. Plastic particle ingestion by wild freshwater fish: A critical review [J]. Environmental Science & Technology, 2019, 53 (22): 12974-12988

[18] Yao L M, Hui L, Yang Z, et al. Freshwater microplastics pollution: Detecting and visualizing emerging trends based on Citespace Ⅱ [J]. Chemosphere, 2020, 245: 125627

[19] Sequeira I F, Prata J C, da Costa J P, et al. Worldwide contamination of fish with microplastics: A brief global overview [J]. Marine Pollution Bulletin, 2020, 160: 111681

[20] Zhang K, Xiong X, Hu H J, et al. Occurrence and characteristics of microplastic pollution in Xiangxi Bay of Three Gorges Reservoir, China [J]. Environmental Science & Technology, 2017, 51(7): 3794-3801

[21] Zheng K, Fan Y J, Zhu Z W, et al. Occurrence and species-specific distribution of plastic debris in wild freshwater fish from the Pearl River catchment, China [J]. Environmental Toxicology and Chemistry, 2019, 38(7): 1504-1513

[22] Su L, Deng H, Li B W, et al. The occurrence of microplastic in specific organs in commercially caught fishes from coast and estuary area of East China [J]. Journal of Hazardous Materials, 2019, 365: 716-724

[23] Devi S S, Sreedevi A V, Kumar A B. First report of microplastic ingestion by the alien fish Pirapitinga (*Piaractus brachypomus*) in the Ramsar site Vembanad Lake, South India [J]. Marine Pollution Bulletin, 2020, 160: 111637

[24] Biginagwa F J, Mayoma B S, Shashoua Y, et al. First evidence of microplastics in the African Great Lakes: Recovery from Lake Victoria Nile perch and Nile tilapia [J]. Journal of Great Lakes Research, 2016, 42(1): 146-149

[25] Peters C A, Bratton S P. Urbanization is a major influence on microplastic ingestion by sunfish in the Brazos River Basin, Central Texas, USA [J]. Environmental Pollution, 2016, 210: 380-387

[26] Andrade M C, Winemiller K O, Barbosa P S, et al. First account of plastic pollution impacting freshwater fishes in the Amazon: Ingestion of plastic debris by piranhas and other serrasalmids with diverse feeding habits [J]. Environmental Pollution, 2019, 244: 766-773

[27] Silva-Cavalcanti J S, Silva J D B, de França E J, et al. Microplastics ingestion by a common tropical freshwater fishing resource [J]. Environmental Pollution, 2017, 221: 218-226

[28] Urbanski B Q, Denadai A C, Azevedo-Santos V M, et al. First record of plastic ingestion by an important commercial native fish (*Prochilodus lineatus*) in the middle Tietê River Basin, Southeast Brazil [J]. Biota Neotropica, 2020, 20(3): e20201005

[29] Zhu L, Wang H, Chen B J, et al. Microplastic ingestion in deep-sea fish from the South China Sea [J]. Science of the Total Environment, 2019, 677: 493-501

[30] Zhang C N, Wang S D, Pan Z K, et al. Occurrence and distribution of microplastics in commercial fishes from estuarine areas of Guangdong, South China [J]. Chemosphere, 2020, 260: 127656

[31] Sathish M N, Jeyasanta I, Patterson J. Occurrence of microplastics in epipelagic and mesopelagic fishes from tuticorin, southeast coast of India [J]. Science of the Total Environment, 2020, 720: 137614

[32] Halstead J E, Smith J A, Carter E A, et al. Assessment tools for microplastics and natural fibres ingested by fish in an urbanised estuary [J]. Environmental Pollution, 2018, 234: 552-561

[33] Zakeri M, Naji A, Akbarzadeh A, et al. Microplastic ingestion in important commercial fish in the southern Caspian Sea [J]. Marine Pollution Bulletin, 2020, 160: 111598

[34] Bagheri T, Gholizadeh M, Abarghouei S, et al. Microplastics distribution, abundance and composition in sediment, fishes and benthic organisms of the Gorgan Bay, Caspian Sea [J]. Chemosphere, 2020, 257: 127201

[35] Güven O, Gökdağ K, Jovanović B, et al. Microplastic litter composition of the Turkish territorial waters of the Mediterranean Sea, and its occurrence in the gastrointestinal tract of fish [J]. Environmental Pollution, 2017, 223: 286-294

[36] Giani D, Baini M, Galli M, et al. Microplastics occurrence in edible fish species (*Mullus barbatus* and *Merluccius merluccius*) collected in three different geographical subareas of the Mediterranean Sea [J]. Marine Pollution Bulletin, 2019, 140: 129-137

[37] Alomar C, Deudero S. Evidence of microplastic ingestion

in the shark *Galeus melastomus* Rafinesque, 1810 in the continental shelf off the western Mediterranean Sea [J]. Environmental Pollution, 2017, 223: 223-229

[38] Tsangaris C, Digka N, Valente T, et al. Using *Boops boops* (Osteichthyes) to assess microplastic ingestion in the Mediterranean Sea [J]. Marine Pollution Bulletin, 2020, 158: 111397

[39] Nadal M A, Alomar C, Deudero S. High levels of microplastic ingestion by the semipelagic fish bogue *Boops boops* (L.) around the Balearic Islands [J]. Environmental Pollution, 2016, 214: 517-523

[40] Bellas J, Martínez-Armental J, Martínez-Cámara A, et al. Ingestion of microplastics by demersal fish from the Spanish Atlantic and Mediterranean coasts [J]. Marine Pollution Bulletin, 2016, 109(1): 55-60

[41] Bessa F, Barría P, Neto J M, et al. Occurrence of microplastics in commercial fish from a natural estuarine environment [J]. Marine Pollution Bulletin, 2018, 128: 575-584

[42] Steer M, Cole M, Thompson R C, et al. Microplastic ingestion in fish larvae in the western English Channel [J]. Environmental Pollution, 2017, 226: 250-259

[43] Rummel C D, Löder M G J, Fricke N F, et al. Plastic ingestion by pelagic and demersal fish from the North Sea and Baltic Sea [J]. Marine Pollution Bulletin, 2016, 102 (1): 134-141

[44] Naidoo T, Sershen, Thompson R C, et al. Quantification and characterisation of microplastics ingested by selected juvenile fish species associated with mangroves in KwaZulu-Natal, South Africa [J]. Environmental Pollution, 2020, 257: 113635

[45] Adika S A, Mahu E, Crane R, et al. Microplastic ingestion by pelagic and demersal fish species from the Eastern Central Atlantic Ocean, off the Coast of Ghana [J]. Marine Pollution Bulletin, 2020, 153: 110998

[46] Vendel A L, Bessa F, Alves V E N, et al. Widespread microplastic ingestion by fish assemblages in tropical estuaries subjected to anthropogenic pressures [J]. Marine Pollution Bulletin, 2017, 117(1-2): 448-455

[47] Parker B W, Beckingham B A, Ingram B C, et al. Microplastic and tire wear particle occurrence in fishes from an urban estuary: Influence of feeding characteristics on exposure risk [J]. Marine Pollution Bulletin, 2020, 160: 111539

[48] Liboiron M, Melvin J, Richárd N, et al. Low incidence of plastic ingestion among three fish species significant for human consumption on the island of Newfoundland, Canada [J]. Marine Pollution Bulletin, 2019, 141: 244-248

[49] Bermúdez-Guzmán L, Alpízar-Villalobos C, Gatgens-García J, et al. Microplastic ingestion by a herring *Opisthonema* sp. in the Pacific coast of Costa Rica [J]. Regional Studies in Marine Science, 2020, 38: 101367

[50] Garnier Y, Jacob H, Guerra A S, et al. Evaluation of microplastic ingestion by tropical fish from Moorea Island, French Polynesia [J]. Marine Pollution Bulletin, 2019, 140: 165-170

[51] Kühn S, Schaafsma F L, van Werven B, et al. Plastic ingestion by juvenile polar cod (*Boreogadus saida*) in the Arctic Ocean [J]. Polar Biology, 2018, 41(6): 1269-1278

[52] van Raamsdonk L W D, van der Zande M, Koelmans A A, et al. Current insights into monitoring, bioaccumulation, and potential health effects of microplastics present in the food chain [J]. Foods, 2020, 9(1): 72

[53] Müller C, Erzini K, Teodósio M A, et al. Assessing microplastic uptake and impact on omnivorous juvenile white seabream *Diplodus sargus* (Linnaeus, 1758) under laboratory conditions [J]. Marine Pollution Bulletin, 2020, 157: 111162

[54] Messinetti S, Mercurio S, Scarì G, et al. Ingested microscopic plastics translocate from the gut cavity of juveniles of the ascidian *Ciona intestinalis* [J]. The European Zoological Journal, 2019, 86(1): 189-195

[55] Hu L L, Chernick M, Lewis A M, et al. Chronic microfiber exposure in adult Japanese medaka (*Oryzias latipes*) [J]. PLoS One, 2020, 15(3): e0229962

[56] Jin Y X, Xia J Z, Pan Z H, et al. Polystyrene microplastics induce microbiota dysbiosis and inflammation in the gut of adult zebrafish [J]. Environmental Pollution, 2018, 235: 322-329

[57] Batel A, Borchert F, Reinwald H, et al. Microplastic accumulation patterns and transfer of benzo[a]pyrene to adult zebrafish (*Danio rerio*) gills and zebrafish embryos [J]. Environmental Pollution, 2018, 235: 918-930

[58] Ding J N, Huang Y J, Liu S J, et al. Toxicological effects of nano- and micro-polystyrene plastics on red tilapia: Are larger plastic particles more harmless? [J]. Journal of Hazardous Materials, 2020, 396: 122693

[59] Yang H, Xiong H R, Mi K H, et al. Toxicity comparison of nano-sized and micron-sized microplastics to goldfish *Carassius auratus* larvae [J]. Journal of Hazardous Materials, 2020, 388: 122058

[60] Koelmans A A, Mohamed Nor N H, Hermsen E, et al. Microplastics in freshwaters and drinking water: Critical review and assessment of data quality [J]. Water Research, 2019, 155: 410-422

[61] Guzzetti E, Sureda A, Tejada S, et al. Microplastic in ma-

rine organism: Environmental and toxicological effects [J]. Environmental Toxicology and Pharmacology, 2018, 64: 164-171

[62] Ferreira P, Fonte E, Soares M E, et al. Effects of multi-stressors on juveniles of the marine fish *Pomatoschistus microps*: Gold nanoparticles, microplastics and temperature [J]. Aquatic Toxicology, 2016, 170: 89-103

[63] Wen B, Jin S R, Chen Z Z, et al. Single and combined effects of microplastics and cadmium on the cadmium accumulation, antioxidant defence and innate immunity of the discus fish (*Symphysodon aequifasciatus*) [J]. Environmental Pollution, 2018, 243: 462-471

[64] Khan F R, Syberg K, Shashoua Y, et al. Influence of polyethylene microplastic beads on the uptake and localization of silver in zebrafish (*Danio rerio*) [J]. Environmental Pollution, 2015, 206: 73-79

[65] Yan W, Hamid N, Deng S, et al. Individual and combined toxicogenetic effects of microplastics and heavy metals (Cd, Pb, and Zn) perturb gut microbiota homeostasis and gonadal development in marine medaka (*Oryzias melastigma*) [J]. Journal of Hazardous Materials, 2020, 397: 122795

[66] Roda J F B, Lauer M M, Risso W E, et al. Microplastics and copper effects on the neotropical teleost *Prochilodus lineatus*: Is there any interaction? [J]. Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology, 2020, 242: 110659

[67] Bussolaro D, Wright S L, Schnell S, et al. Co-exposure to polystyrene plastic beads and polycyclic aromatic hydrocarbon contaminants in fish gill (RTgill-W1) and intestinal (RTgutGC) epithelial cells derived from rainbow trout (*Oncorhynchus mykiss*) [J]. Environmental Pollution, 2019, 248: 706-714

[68] Granby K, Rainieri S, Rasmussen R R, et al. The influence of microplastics and halogenated contaminants in feed on toxicokinetics and gene expression in European seabass (*Dicentrarchus labrax*) [J]. Environmental Research, 2018, 164: 430-443

[69] Oliveira M, Ribeiro A, Hylland K, et al. Single and combined effects of microplastics and pyrene on juveniles (0+ Group) of The Common Goby *Pomatoschistus microps* (Teleostei, Gobiidae) [J]. Ecological Indicators, 2013, 34: 641-647

[70] Qiao R X, Lu K, Deng Y F, et al. Combined effects of polystyrene microplastics and natural organic matter on the accumulation and toxicity of copper in zebrafish [J]. Science of the Total Environment, 2019, 682: 128-137

[71] Grigorakis S, Drouillard K G. Effect of microplastic amendment to food on diet assimilation efficiencies of PCBs by fish [J]. Environmental Science & Technology, 2018, 52(18): 10796-10802

[72] Barboza L G A, Vieira L R, Guilhermino L. Single and combined effects of microplastics and mercury on juveniles of the European seabass (*Dicentrarchus labrax*): Changes in behavioural responses and reduction of swimming velocity and resistance time [J]. Environmental Pollution, 2018, 236: 1014-1019

[73] Garcia-Garin O, Vighi M, Sala B, et al. Assessment of organophosphate flame retardants in Mediterranean *Boops boops* and their relationship to anthropization levels and microplastic ingestion [J]. Chemosphere, 2020, 252: 126569

[74] Cuq B, Gontard N, Cuq J L, et al. Selected functional properties of fish myofibrillar protein-based films as affected by hydrophilic plasticizers [J]. Journal of Agricultural and Food Chemistry, 1997, 45(3): 622-626

[75] Critchell K, Hoogenboom M O. Effects of microplastic exposure on the body condition and behaviour of planktivorous reef fish (*Acanthochromis polyacanthus*) [J]. PLoS One, 2018, 13(3): e0193308

[76] Naidoo T, Glassom D. Decreased growth and survival in small juvenile fish, after chronic exposure to environmentally relevant concentrations of microplastic [J]. Marine Pollution Bulletin, 2019, 145: 254-259

[77] Nanninga G B, Scott A, Manica A. Microplastic ingestion rates are phenotype-dependent in juvenile anemonefish [J]. Environmental Pollution, 2020, 259: 113855

[78] Grigorakis S, Mason S A, Drouillard K G. Determination of the gut retention of plastic microbeads and microfibers in goldfish (*Carassius auratus*) [J]. Chemosphere, 2017, 169: 233-238

[79] Iheanacho S C, Odo G E. Dietary exposure to polyvinyl chloride microparticles induced oxidative stress and hepatic damage in *Clarias gariepinus* (Burchell, 1822) [J]. Environmental Science and Pollution Research, 2020, 27 (17): 21159-21173

[80] Iheanacho S C, Odo G E. Neurotoxicity, oxidative stress biomarkers and haematological responses in African catfish (*Clarias gariepinus*) exposed to polyvinyl chloride microparticles [J]. Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology, 2020, 232: 108741

[81] Huuskonen H, Subiron i Folguera J, Kortet R, et al. Do whitefish (*Coregonus lavaretus*) larvae show adaptive variation in the avoidance of microplastic ingestion? [J]. Environmental Pollution, 2020, 262: 114353

[82] Banaee M, Soltanian S, Sureda A, et al. Evaluation of single and combined effects of cadmium and micro-plastic particles on biochemical and immunological parameters of common carp (*Cyprinus carpio*) [J]. Chemosphere, 2019, 236: 124335

[83] Xia X H, Sun M H, Zhou M, et al. Polyvinyl chloride microplastics induce growth inhibition and oxidative stress in *Cyprinus carpio* var. larvae [J]. Science of the Total Environment, 2020, 716: 136479

[84] Choi J S, Jung Y J, Hong N H, et al. Toxicological effects of irregularly shaped and spherical microplastics in a marine teleost, the sheepshead minnow (*Cyprinodon variegatus*) [J]. Marine Pollution Bulletin, 2018, 129(1): 231-240

[85] de Sales-Ribeiro C, Brito-Casillas Y, Fernandez A, et al. An end to the controversy over the microscopic detection and effects of pristine microplastics in fish organs [J]. Scientific Reports, 2020, 10: 12434

[86] Kurchaba N, Cassone B J, Northam C, et al. Effects of MP polyethylene microparticles on microbiome and inflammatory response of larval zebrafish [J]. Toxics, 2020, 8(3): 55

[87] Mak C W, Ching-Fong Yeung K, Chan K M. Acute toxic effects of polyethylene microplastic on adult zebrafish [J]. Ecotoxicology and Environmental Safety, 2019, 182: 109442

[88] Kim S W, Chae Y, Kim D, et al. Zebrafish can recognize microplastics as inedible materials: Quantitative evidence of ingestion behavior [J]. The Science of the Total Environment, 2019, 649: 156-162

[89] LeMoine C M R, Kelleher B M, Lagarde R, et al. Transcriptional effects of polyethylene microplastics ingestion in developing zebrafish (*Danio rerio*) [J]. Environmental Pollution, 2018, 243(Pt A): 591-600

[90] Cormier B, Batel A, Cachot J, et al. Multi-laboratory hazard assessment of contaminated microplastic particles by means of enhanced fish embryo test with the zebrafish (*Danio rerio*) [J]. Frontiers in Environmental Science, 2019, 7: 135

[91] Boyle D, Catarino A I, Clark N J, et al. Polyvinyl chloride (PVC) plastic fragments release Pb additives that are bioavailable in zebrafish [J]. Environmental Pollution, 2020, 263: 114422

[92] Sarasamma S, Audira G, Siregar P, et al. Nanoplastics cause neurobehavioral impairments, reproductive and oxidative damages, and biomarker responses in zebrafish: Throwing up alarms of wide spread health risk of exposure [J]. International Journal of Molecular Sciences, 2020, 21(4): 1410

[93] Lu Y F, Zhang Y, Deng Y F, et al. Uptake and accumulation of polystyrene microplastics in zebrafish (*Danio rerio*) and toxic effects in liver [J]. Environmental Science & Technology, 2016, 50(7): 4054-4060

[94] Qiang L Y, Lo L S H, Gao Y, et al. Parental exposure to polystyrene microplastics at environmentally relevant concentrations has negligible transgenerational effects on zebrafish (*Danio rerio*) [J]. Ecotoxicology and Environmental Safety, 2020, 206: 111382

[95] Gu L Q, Tian L, Gao G, et al. Inhibitory effects of polystyrene microplastics on caudal fin regeneration in zebrafish larvae [J]. Environmental Pollution, 2020, 266: 114664

[96] Chen Q Q, Lackmann C, Wang W Y, et al. Microplastics lead to hyperactive swimming behaviour in adult zebrafish [J]. Aquatic Toxicology, 2020, 224: 105521

[97] Qiao R X, Deng Y F, Zhang S H, et al. Accumulation of different shapes of microplastics initiates intestinal injury and gut microbiota dysbiosis in the gut of zebrafish [J]. Chemosphere, 2019, 236: 124334

[98] Mazurais D, Ernande B, Quazuguel P, et al. Evaluation of the impact of polyethylene microbeads ingestion in European Sea bass (*Dicentrarchus labrax*) larvae [J]. Marine Environmental Research, 2015, 112: 78-85

[99] Espinosa C, García Beltrán J M, Esteban M A, et al. *In vitro* effects of virgin microplastics on fish head-kidney leucocyte activities [J]. Environmental Pollution, 2018, 235: 30-38

[100] Wang X, Zheng H, Zhao J, et al. Photodegradation elevated the toxicity of polystyrene microplastics to grouper (*Epinephelus moara)* through disrupting hepatic lipid homeostasis [J]. Environmental Science & Technology, 2020, 54(10): 6202-6212

[101] Bour A, Hossain S, Taylor M, et al. Synthetic microfiber and microbead exposure and retention time in model aquatic species under different exposure scenarios [J]. Frontiers in Environmental Science, 2020, 8: 83

[102] Ahrendt C, Perez-Venegas D J, Urbina M, et al. Microplastic ingestion cause intestinal lesions in the intertidal fish *Girella laevifrons* [J]. Marine Pollution Bulletin, 2020, 151: 110795

[103] Guven O, Bach L, Munk P, et al. Microplastic does not magnify the acute effect of PAH pyrene on predatory performance of a tropical fish (*Lates calcarifer*) [J]. Aquatic Toxicology, 2018, 198: 287-293

[104] Qu H, Ma R X, Wang B, et al. Enantiospecific toxicity, distribution and bioaccumulation of chiral antidepressant venlafaxine and its metabolite in loach (*Misgurnus anguil-*

licaudatus) co-exposed to microplastic and the drugs [J]. Journal of Hazardous Materials, 2019, 370: 203-211

[105] Khan F R, Boyle D, Chang E, et al. Do polyethylene microplastic beads alter the intestinal uptake of Ag in rainbow trout (*Oncorhynchus mykiss*)? Analysis of the MP vector effect using *in vitro* gut sacs [J]. Environmental Pollution, 2017, 231(Pt 1): 200-206

[106] Ašmonait G, Larsson K, Undeland I, et al. Size matters: Ingestion of relatively large microplastics contaminated with environmental pollutants posed little risk for fish health and fillet quality [J]. Environmental Science & Technology, 2018, 52(24): 14381-14391

[107] Pannetier P, Morin B, le Bihanic F, et al. Environmental samples of microplastics induce significant toxic effects in fish larvae [J]. Environment International, 2020, 134: 105047

[108] Rochman C M, Kurobe T, Flores I, et al. Early warning signs of endocrine disruption in adult fish from the ingestion of polyethylene with and without sorbed chemical pollutants from the marine environment [J]. Science of the Total Environment, 2014, 493: 656-661

[109] Cong Y, Jin F, Tian M, et al. Ingestion, egestion and post-exposure effects of polystyrene microspheres on marine medaka (*Oryzias melastigma*) [J]. Chemosphere, 2019, 228: 93-100

[110] Chen J C, Chen M Y, Fang C, et al. Microplastics negatively impact embryogenesis and modulate the immune response of the marine medaka *Oryzias melastigma* [J]. Marine Pollution Bulletin, 2020, 158: 111349

[111] Wang J, Li Y J, Lu L, et al. Polystyrene microplastics cause tissue damages, sex-specific reproductive disruption and transgenerational effects in marine medaka (*Oryzias melastigma*) [J]. Environmental Pollution, 2019, 254: 113024

[112] Malinich T D, Chou N, Sepúlveda M S, et al. No evidence of microplastic impacts on consumption or growth of larval *Pimephales promelas* [J]. Environmental Toxicology and Chemistry, 2018, 37(11): 2912-2918

[113] Greven A C, Merk T, Karagöz F, et al. Polycarbonate and polystyrene nanoplastic particles act as stressors to the innate immune system of fathead minnow (*Pimephales promelas*) [J]. Environmental Toxicology and Chemistry, 2016, 35(12): 3093-3100

[114] LaPlaca S B, Hurk P. Toxicological effects of micronized tire crumb rubber on mummichog (*Fundulus heteroclitus*) and fathead minnow (*Pimephales promelas*) [J]. Ecotoxicology, 2020, 29(5): 524-534

[115] Jakubowska M, Białowąs M, Stankevičiūtė M, et al. Effects of chronic exposure to microplastics of different polymer types on early life stages of sea trout *Salmo trutta* [J]. Science of the Total Environment, 2020, 740: 139922

[116] Ory N C, Gallardo C, Lenz M, et al. Capture, swallowing, and egestion of microplastics by a planktivorous juvenile fish [J]. Environmental Pollution, 2018, 240: 566-573

[117] Jovanovi B, Gökda K, Güven O, et al. Virgin microplastics are not causing imminent harm to fish after dietary exposure [J]. Marine Pollution Bulletin, 2018, 130: 123-131

[118] Batel A, Baumann L, Carteny C C, et al. Histological, enzymatic and chemical analyses of the potential effects of differently sized microplastic particles upon long-term ingestion in zebrafish (*Danio rerio*) [J]. Marine Pollution Bulletin, 2020, 153: 111022

[119] Mbedzi R, Dalu T, Wasserman R J, et al. Functional response quantifies microplastic uptake by a widespread African fish species [J]. The Science of the Total Environment, 2020, 700: 134522

[120] Sharifinia M, Bahmanbeigloo Z A, Keshavarzifard M, et al. Microplastic pollution as a grand challenge in marine research: A closer look at their adverse impacts on the immune and reproductive systems [J]. Ecotoxicology and Environmental Safety, 2020, 204: 111109

[121] Espinosa C, Cuesta A, Esteban M Á. Effects of dietary polyvinylchloride microparticles on general health, immune status and expression of several genes related to stress in gilthead seabream (*Sparus aurata* L.) [J]. Fish & Shellfish Immunology, 2017, 68: 251-259

[122] Cedervall T, Hansson L A, Lard M, et al. Food chain transport of nanoparticles affects behaviour and fat metabolism in fish [J]. PLoS One, 2012, 7(2): e32254

[123] Zhao H J, Xu J K, Yan Z H, et al. Microplastics enhance the developmental toxicity of synthetic phenolic antioxidants by disturbing the thyroid function and metabolism in developing zebrafish [J]. Environment International, 2020, 140: 105750

[124] Wen B, Zhang N, Jin S R, et al. Microplastics have a more profound impact than elevated temperatures on the predatory performance, digestion and energy metabolism of an Amazonian cichlid [J]. Aquatic Toxicology, 2018, 195: 67-76

[125] McCormick M I, Chivers D P, Ferrari M C O, et al. Microplastic exposure interacts with habitat degradation to affect behaviour and survival of juvenile fish in the field [J]. Proceedings Biological Sciences, 2020, 287(1937): 20201947

[126] Greene D. Lipid metabolism in fish [J]. Progress in Lipid Research, 1987, 26(1): 53-85

[127] Pedà C, Caccamo L, Fossi M C, et al. Intestinal alterations in European Sea bass *Dicentrarchus labrax* (Linnaeus, 1758) exposed to microplastics: Preliminary results [J]. Environmental Pollution, 2016, 212: 251-256

[128] O'Hara A M, Shanahan F. The gut flora as a forgotten organ [J]. EMBO Reports, 2006, 7(7): 688-693

[129] Hwang J, Choi D, Han S, et al. An assessment of the toxicity of polypropylene microplastics in human derived cells [J]. Science of the Total Environment, 2019, 684: 657-669

[130] Zhang X, Wen K, Ding D X, et al. Size-dependent adverse effects of microplastics on intestinal microbiota and metabolic homeostasis in the marine medaka (*Oryzias melastigma*) [J]. Environment International, 2021, 151: 106452

[131] Pratte Z A, Besson M, Hollman R D, et al. The gills of reef fish support a distinct microbiome influenced by host-specific factors [J]. Applied and Environmental Microbiology, 2018, 84(9): e00018-e00063

[132] Koongolla J B, Lin L, Pan Y F, et al. Occurrence of microplastics in gastrointestinal tracts and gills of fish from Beibu Gulf, South China Sea [J]. Environmental Pollution, 2020, 258: 113734

[133] Yu Q, Hu X J, Yang B, et al. Distribution, abundance and risks of microplastics in the environment [J]. Chemosphere, 2020, 249: 126059

[134] Hoang T C, Felix-Kim M. Microplastic consumption and excretion by fathead minnows (*Pimephales promelas*): Influence of particles size and body shape of fish [J]. Science of the Total Environment, 2020, 704: 135433

[135] Zhang F, Wang X H, Xu J Y, et al. Food-web transfer of microplastics between wild caught fish and crustaceans in East China Sea [J]. Marine Pollution Bulletin, 2019, 146: 173-182

[136] Lenz R, Enders K, Nielsen T G. Microplastic exposure studies should be environmentally realistic [J]. PNAS, 2016, 113(29): 4121-4122

[137] Fu Z L, Chen G L, Wang W J, et al. Microplastic pollution research methodologies, abundance, characteristics and risk assessments for aquatic biota in China [J]. Environmental Pollution, 2020, 266: 115098 ◆