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微纳米塑料对鱼类的毒性效应及作用机制研究进展

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摘要: 微纳米塑料(MNPs)在水环境中的污染问题已成为全球关注的热点。MNPs 因其数量多、粒径小,极易被鱼类误食对鱼体造成危害。本文综述了 MNPs 对鱼类毒性效应及作用机制,首先阐述了鱼类对 MNPs 的摄食、富集和转运规律,分析了不同粒径的 MNPs 对鱼类造成的不同危害,其次重点评述了 MNPs 对鱼类毒性效应及作用机制,并介绍了 MNPs 和其他污染物对鱼类的毒性效应,最后展望了 MNPs 对鱼类的研究趋势。研究 MNPs 对鱼类毒性效应及作用机制有利于增进对 MNPs 的生态毒性的认识,为经济鱼类的安全生产和生态稳定提供科学依据。

关键词: 微纳塑料;鱼类;毒性效应;作用机制

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Research Advances on Toxic Effects and Mechanisms of Micro- and Nano-plastics on Fish

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Abstract: The pollution of micro- and nano-plastics (MNPs) in water environments has become a global concern. Because of their large quantity and small particle size, MNPs are prone to be ingested by fish and cause harm. This article reviews the toxic effects and the mechanisms of MNPs on fish. Firstly, the patterns of MNPs ingestion, enrichment, and transport in fish are summarized, and the stress caused by MNPs with different particle sizes are analyzed. Secondly, the toxic effects of MNPs on fish and the mechanisms are emphatically demonstrated, and the combined toxic effects of MNPs and other pollutants on fish are delineated. Finally, three research prospects of MNPs on fish are proposed. This review article is conducive to enhancing the understanding of the ecotoxicity of MNPs, providing scientific basis for the safe production and ecological stability of commercial fish.

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塑料制品被广泛运用于各行各业中,但大量的废弃塑料难以充分回收利用而被丢弃进入水环境中[1]。近年来,塑料污染已成为全球性的环境问题[2]。微塑料(microplastics, MPs)指直径<5 mm 的塑料颗粒,纳米塑料(nanoplastics, NPs)指颗粒直径 1 ~ 100 nm 的塑料颗粒[3]。微塑料和纳米塑料颗粒统称为微纳塑料(micro- and nano-plastics, MNPs)。MNPs 数量多、粒径小,水生生物误食后可能会影响其进食习惯,损害胃肠道导致食物摄入量减少[4]。同时,MNPs 具有大的比表面积和疏水特性,造成许多污染物在其表面累积,并使这些污染物在食物网的较高营养级富集[5]。值得关注的是,MNPs 粒径差异可能会引起鱼体内不同程度毒性效应,粒径更小的 NPs 可能会穿透细胞膜进入循环系统而对鱼体全身器官形成危害[6]。早期,当确认 MNPs 污染的严重性时,人们只关注 MNPs 污染造成的物理损伤的情况,随着研究的不断深入,人们越来越关注 MNPs 污染造成的化学及生理损伤[7]。

目前,国际上发表了大量关于 MNPs 对水生环境中鱼类的毒性效应研究的文章,研究者通过病理技术和组学等,从细胞和分子角度来探讨 MNPs 对鱼类的毒性效用。组学指的是转录组学、蛋白质组学、微生物组学、代谢组学等一些种类个体的系统集合方法。但目前的相关文章只注重某一方面的报道,并没有进行系统整理和总结。本文系统地整理了鱼类对 MNPs 的摄食、富集和转运规律,在此基础上,论述了 MNPs 的粒径作用差异,并着重分析了 MNPs 对鱼类毒性效应及作用机制,也介绍了 MNPs 和其他污染物对鱼类的毒性效应,最后对未来 MNPs 的研究方向进行了展望。

1 鱼类对 MNPs 的摄取、富集和转运(Uptake, enrichment and transport of MNPs in fish)

MNPs 存在整个水生态系统中,由于粒径小、数量多,很容易被水中鱼类误食[8]。摄入的 MNPs 会在鱼体内富集,存在于鱼类的胃肠道系统或迁移到其他组织中[9]。目前由于检测手段有限,绝大多数研究只观测到微米级塑料。表 1 中罗列了不同鱼类肌肉和肝脏中的 MPs 分布[6]。Contino 等[10]研究发现粒径为 50 nm 和 100 nm 的 MNPs 在斑马鱼(*Danio rerio*)的头部积累,尤其是在眼睛中。Pradit 等[11]的报道指出,MNPs 可以在骨颊海鲇(*Osteogeneiosus militaris*)体内积累,最常见于胃,其次是肌肉组织和鳃。海水青鳉鱼(*Oryzias melastigma*)在环境相关浓度 MNPs 暴露 60 d 后,MNPs 在其鳃、肠道和肝脏中积累,在 2 μg·L^{-1}暴露组中,肠道和鳃中的 MNPs 浓度分别为(18.33±3.40) 个·鱼$^{-1}$和(39.06±7.26) 个·鱼$^{-1}$。此外,在 20 μg·L^{-1}和 200 μg·L^{-1}暴露组中,肠道和鳃中的 MNPs 浓度相似,平均值分别为 73 个·鱼$^{-1}$和 175 个·鱼$^{-1}$。在 2、20 和 200 μg·L^{-1}暴露组中,肝脏中的 MNPs 浓度分别为(3.3±1.3)、(4.1±0.8)和(8.0±1.6) 个·鱼$^{-1}$[12]。金头鲷(*Sparus aurata*)在 6 种常见 MNPs 暴露 45 d 后,MNPs 在胃肠道中的滞留率相当低,但一些大颗粒仍滞留在肝脏中,分析的所有肝脏中有 5.3% 含有至少一个 MNPs[13]。东北大西洋 3 种重要商业鱼类的胃肠道、鳃中都发现了 MNPs,在 150 条被检查的鱼中,有 73 条鱼(49%)发现了 MNPs,其中 52 条鱼(35%)在胃肠道中有 MNPs,54 条鱼(36%)在鳃中有 MNPs,48 条鱼(32%)在背肌中有 MNPs[14]。中国沿海河口地区花鲈(*Lateolabrax maculatus*)的肠道和鳃中也检测到了 MNPs,肠道中的 MNPs 丰度为 0.3 ~ 5.3 个·鱼$^{-1}$,鳃中的 MNPs 丰度为 0.3 ~ 2.6 个·鱼$^{-1}$。鳃中 MNPs 的尺寸小于肠道中的 MNPs[15]。

MNPs 还可以通过食物网向高营养级的生物传播[16]。Ma 和 You[17] 以中国白洋淀为例,建立了 MNPs 在水生食物网中的累积效应模型;结果表明,MNPs 在整个食物网中快速扩散和累积,最终到达高营养级水生生物——乌鳢(*Channa argus*)。对我国东海舟山渔场捕获的 11 种野生鱼类(193 条)和 8 种野生甲壳类(136 条)的 MNPs 污染情况研究表明,MNPs 在东海水体及鱼体中无处不在,且 MNPs 主要聚集在整个海洋食物网中营养级较高的鱼类中[18]。在加拿大安大略省锡姆科湖 7 种游钓鱼类的胃肠道、鱼肉片和肝脏中广泛存在着 MNPs。与体型较小的鱼相比,体型较大的鱼的 MNPs 负荷较高[19]。目前科学家已经在鱼类中广泛检测到 MNPs 的存在,但在 MNPs 在鱼类食物链传递的研究较为缺乏。

2 MNPs 的粒径作用差异(Particle size difference of MNPs)

MNPs 可能有意地被添加到产品中(如清洁用品中的微珠),也可以在尺寸较大的塑料分解时形成(如海洋中的塑料垃圾)[20]。粒径大小是 MNPs 最显

表 1　不同鱼类肌肉和肝脏中的微塑料(MPs)分布[6]

Table 1　Microplastics (MPs) distribution in muscle and liver of different fish[6]

种类 Species	样本数量 Sample size	MPs 分布 MPs distribution		MPs 性状 MPs trait		
		肝脏 Liver	肌肉 Muscle	形状 Shape	尺寸 Dimension	组成 Composition
欧洲鳀 (*Engraulis encrasicolus*)	10	1.125 items·individual^{-1}	NA	碎片 Fragment	124～438 μm, (323±101) μm	PE
鲬 (*Platycephalus indicus*)	12	1.08 items·individual^{-1}	4.58 items·individual^{-1}	纤维 Fiber	肝脏:<250 μm;肌肉:<100 μm (大多数) Liver: <250 μm; Muscle: <100 μm (Most)	NA
多齿蛇鲻 (*Saurida tumbil*)	4	4.25 items·individual^{-1}	3.00 items·individual^{-1}	纤维 Fiber	肝脏:<250 μm;肌肉:250～500 μm (大多数) Liver: <250 μm; Muscle: 250～500 μm (Most)	NA
沙尖鱼 (*Sillago sihama*)	17	1.94 items·individual^{-1}	3.76 items·individual^{-1}	纤维 Fiber	肝脏:<250 μm;肌肉:<100 μm (大多数) Liver: <250 μm; Muscle: <100 μm (Most)	NA
短吻三线舌鳎 (*Cynoglossus abbreviatus*)	11	3.64 items·individual^{-1}	3.09 items·individual^{-1}	纤维,碎片 Fiber, Fragment	肝脏:<250 μm;肌肉:250～500 μm (大多数) Liver: <250 μm; Muscle: 250～500 μm (Most)	NA
鲬 (*Platycephalus indicus*)	16	NA	(1.85±0.46) items·g^{-1}	纤维,碎片,小球 Fiber, Fragment, Sphere	纤维:>100 μm;碎片:<500 μm;小球:<100 μm Fiber: >100 μm; Fragment: <500 μm; Sphere: <100 μm	NA
斑条魣 (*Sphyraena jello*)	15	NA	(0.57±0.17) items·g^{-1}	纤维,碎片 Fiber, Fragment	纤维:100～5 000 μm;碎片:<500 μm Fiber: 100～5 000 μm; Fragment: <500 μm	NA
点带石斑鱼 (*Epinephelus coioides*)	20	NA	(0.78±0.22) items·g^{-1}	纤维,碎片,小球 Fiber, Fragment, Sphere	纤维:>100 μm;碎片:<500 μm;小球:<100 μm Fiber: >100 μm; Fragment: <500 μm; Sphere: <100 μm	NA
欧洲鲈 (*Dicentrachus labrax*)	50	NA	(0.4±0.7) items·g^{-1}	纤维,碎片 Fiber, Fragment	碎片:<150 μm;纤维:100～3 000 μm Fragment: <150 μm; Fiber: 100～3 000 μm	PE, PES, rayon
黑线鳕 (*Melanogrammus aeglefinus*)	12	NA	0.24 items·g^{-1}	纤维,碎片 Fiber, Fragment	5～5 000 μm	PET

续表1

种类 Species	样本数量 Sample size	MPs分布 MPs distribution		MPs性状 MPs trait		
		肝脏 Liver	肌肉 Muscle	形状 Shape	尺寸 Dimension	组成 Composition
欧洲鲈 (*Dicentrarchus labrax*)	10	NA	0.19 items·g^{-1}	纤维,碎片 Fiber, Fragment	NA	PET, PE
鲽 (*Pleuronectes platessa*)	10	NA	0.77 items·g^{-1}	纤维,碎片,小球,薄膜 Fiber, Fragment, Sphere, Film	NA	PET
大西洋鲭 (*Scromber scombrus*)	10	NA	0.35 items·g^{-1}	纤维,碎片,薄膜 Fiber, Fragment, Film	NA	PET, PP
纹首鮨 (*Serranus scriba*)	40	NA	(1.78±0.26)~(6.03±0.47) items·g^{-1}	碎片 Fragment	<3 μm	PEVA, HDPE
尼罗罗非鱼 (*Oreochromis niloticus*)	18	NA	碎片:2~17 items·g^{-1} Fragment: 2~17 items·g^{-1}	纤维,碎片,薄膜 Fiber, Fragment, Film	NA	PET, PP, nylon
小口黑鲈 (*Smallmouth bass*)	7	(1.5±2.0) items·$individual^{-1}$	(8.2±11.4) items·$individual^{-1}$	纤维,碎片,薄膜,泡沫 Fiber, Fragment, Film, Foam	肌肉:12~5 000 μm;肝脏:71~5 000 μm Muscle: 12~5 000 μm; Liver: 71~5 000 μm	PES, PP, PE
红鲻鱼 (*Mullus barbatus*)	82	NA	0.5 items·$individual^{-1}$	纤维,碎片,小球 Fiber, Fragment, Sphere	50~5 000 μm	PES, nylon, polychloroprene
长体西鲱 (*Alosa immaculata*)	82	NA	0.7 items·$individual^{-1}$	纤维,碎片,小球 Fiber, Fragment, Sphere	NA	NA

注:NA 表示没有发现或原文没有注明;PE 表示聚乙烯,PES 表示聚醚砜,rayon 表示人造丝,PET 表示聚对苯二甲酸乙二醇酯,PP 表示聚丙烯,PEVA 表示聚乙烯-醋酸乙烯酯,HDPE 表示高密度聚乙烯,nylon 表示尼龙,polychloroprene 表示聚氯丁二烯。

Note: NA indicates no discovery or no indication in the original text; PE stands for polyethylene; PES stands for polyether sulfone; PET stands for polyethylene terephthalate; PP stands for polypropylene; PEVA stands for polyethylene vinyl acetate; HDPE stands for high density polyethylene.

著的特点,它对影响 MNPs 的毒性效应起至关重要的作用[21]。

MNPs 的尺寸越小,其穿越生物屏障,渗入鱼类组织的能力越强。例如,在同等浓度(500 mg·L^{-1})条件下,0.5 μm 的聚苯乙烯 MNPs 降低斑马鱼胚胎孵化率,而 10 μm 的聚苯乙烯 MNPs 没有抑制斑马鱼胚胎孵化[22]。在胚胎阶段,胚胎膜允许水分子和氧气等小分子通过膜孔进入膜内,进而对胚胎孵化产生影响,而 10 μm 的聚苯乙烯 MNPs 粒径比较大,胚胎膜能够阻止它进入膜内。Yang 等[23]研究了 70 nm 和 50 μm 的 MNPs 对金鱼(*Carassius auratus*)的毒理效应,结果表明,70 nm 的 MNPs 可以通过金鱼的表皮进入肌肉组织,对肌肉组织造成损害,破坏神经纤维,抑制乙酰胆碱酯酶(AchE)活性,并且对金鱼的毒性效应高于 50 μm MNPs。粒径 42 μm 的 MNPs 可以吸附到青鳉(*Oryzias latipes*)鱼卵的绒毛膜上并积聚;粒径 39.4 nm 的 MNPs 在胚胎发育过程中转移到卵黄和胆囊中[24]。较小的 MNPs 具有较大的比表面积,因此它们更容易被细胞富集。Wang 等[25]考察了 2 种粒径(0.5 μm 和 5 μm)的 MNPs 对泥鳅(*Misgurnus anguillicaudatus*)的影响,结果发现,泥鳅肝脏和肠道中小粒径 MNPs 的富集量高于大粒径 MNPs。斑马鱼在聚苯乙烯 MNPs 中暴露 7 d 后,5 μm MNPs 在鱼鳃、肝脏和肠道中积累,而 20 μm MNPs 仅积累在鱼鳃和肠道中[26]。

MNPs 由于粒径不同,进入鱼体的运输途径也存在差异(图 1)。尤其是胚胎发育过程中,NPs 可通过绒毛膜和表皮渗透进入胚胎,进入的 NPs 随后分布在胚胎卵黄囊,最后迁移到鱼类的其他内部器官。NPs 甚至可以穿透眼睛。而粒径较大的 MPs 只能吸附在胚胎上。幼鱼可自由摄食后,食后的 MNPs 分布于整个鱼体(图 1A)。MNPs 在肠道内的吸收转移方式主要包括内吞作用和细胞渗透,而粒径较大的 MPs 则容易通过纤毛清除过程被排出体外(图 1B)。MNPs 通过多种途径进入成鱼体内,如鳃过滤或口吞吐,鳃过滤能提前筛除大粒径的 MPs,而小粒径的 NPs 则通过血液循环进入动静脉到达心脏、肝脏等鱼体内脏部位(图 1C)。

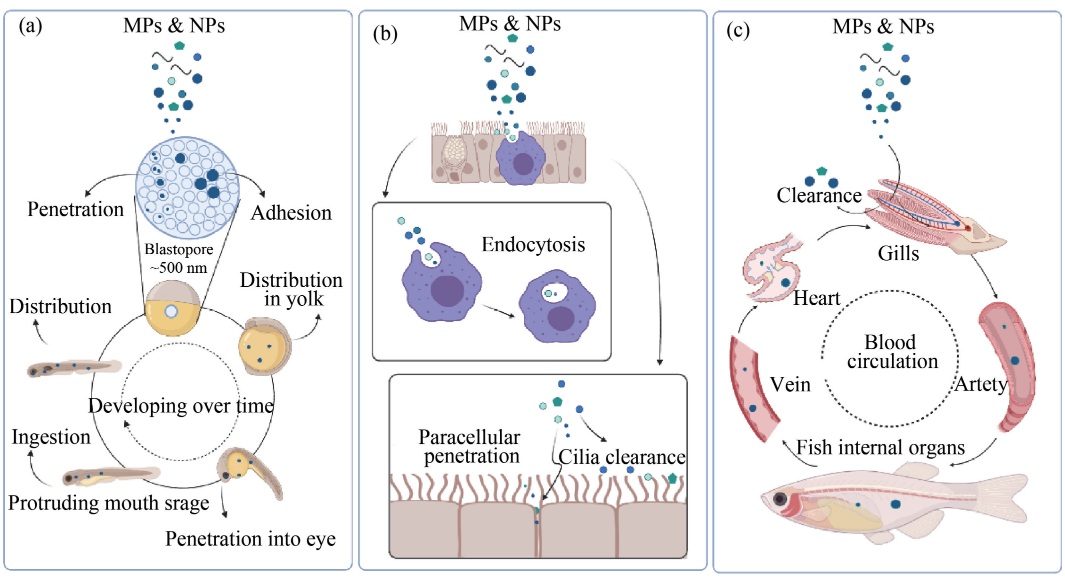

图 1　微纳米塑料(MNPs)进入鱼体的主要运输途径[6]

注:A 图展示胚胎发育过程中 NPs 的易位方式;首先,MNPs 吸附在胚胎上,纳米塑料(NPs)通过绒毛膜和表皮渗透进入胚胎;进入的 NPs 随后分布在胚胎卵黄囊,最后迁移到鱼类的其他内部器官;NPs 甚至可以穿透眼睛;幼鱼可自由摄食后,食后的 MNPs 分布于整个鱼体;B 图展示 MNPs 通过肠道吸收转移,包括内吞作用和细胞渗透;C 图展示 MNPs 通过鳃和血液循环转移。

Fig. 1　Main transport pathways of micro- and nano-plastics (MNPs) into the fish body[6]

Note: Fig.A shows nanoplastics (NPs) translocation ways along with embryonic development; firstly, MNPs adhere to embryos and NPs enter embryos through chorion and epidermis penetration; the penetrated NPs then distributed in the yolk sac of embryos, and finally migrated to other internal organs of fish; NPs can even penetrate into eyes; after larval protruding mouth stage, MNPs distribute to whole fish body after ingestion; Fig.B shows MNPs translocation through intestine absorption, including endocytosis and paracellular penetration; Fig.C shows MNPs translocation through gill and blood circulation.

3 MNPs对鱼类的毒性效应及作用机制(Toxic effects and mechanisms of MNPs on fish)

鱼类是水生食物链中高营养级的消费者,也是人类生活中必不可少的食物,与人类的健康息息相关。鱼类具有较高的生态价值,被广泛应用于水生环境中污染物污染风险评估。因此,MNPs对鱼类的毒性效应及其作用机制的研究受到广泛关注。

3.1 MNPs对鱼类毒性

MNPs被水生环境中的鱼类误食后,对鱼类造成一定的毒害作用,主要包括在死亡率、增长率、氧化应激、炎症反应和基因异常表达等方面的影响[27]。目前,有关MNPs对鱼类毒性方面的研究,主要集中在MNPs对鱼类细胞和分子水平的效应。例如,Usman等[28]发现高浓度的5 μm聚苯乙烯MNPs暴露爪哇青鳉鱼(*Oryzias javanicus*)后,其脑切片出现了水肿,可能是由于氧化应激和氧化损伤所致。Kaloyianni等[29]报道了5~12 μm的聚苯乙烯MNPs对斑马鱼和鲈鱼(*Lateolabrax japonicus*)的影响,结果表明,与对照组相比,2种鱼的肝脏和鳃*caspases*水平都明显增加,暴露于MNPs引发了2种鱼类的肝脏和鳃的细胞凋亡。Wang等[30]将稀有鮈鲫(*Gobiocypris rarus*)暴露于浓度为200 $\mu g \cdot L^{-1}$的1 μm聚苯乙烯MNPs后,通过转录组学发现差异表达基因与细胞生长、细胞死亡和细胞分化等生物反应过程有关。此外,长期暴露于44 nm聚苯乙烯MNPs可以诱导金鱼红细胞的DNA损伤[31]。暴露于聚乙烯MNPs(直径为10~63 μm)会造成青鳉视网膜毛细血管扩张、肾功能恶化和氧化应激的增加(图2)[32]。尖齿胡鲶(*Clarias gariepinus*)暴露于MNPs中,其游泳速度、行驶距离和运动模式均显著降低[33]。综上,研究鱼类对MNPs的吸收、富集和代谢有利于进一步了解MNPs对鱼类产生危害,目前这方面研究仍需深入。

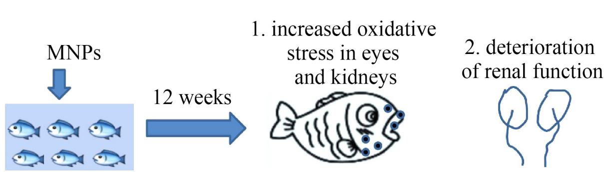

图2 MNPs对青鳉的毒性效应[32]

Fig. 2 Toxic effects of MNPs on medaka[32]

3.2 MNPs对鱼类毒性作用机制

水生环境中的鱼类既可以摄食MNPs,也可以排泄MNPs[34]。当鱼类摄食MNPs后,MNPs主要在肠道中积累[35]。由于MNPs很难降解,进入鱼体后,在肠道的停留时间过长,这就导致了鱼类的摄食量下降、氧化应激和炎症反应等[36]。MNPs对鱼类的毒性作用机制主要有以下几个方面。

(1)对循环和呼吸系统的毒性作用机制。水环境中MNPs被鱼类摄食后,主要在肠道中富集,更小尺寸的MNPs可能转移到循环系统和鱼鳃,从而诱导活性氧(ROS)的产生和细胞凋亡,对循环和呼吸系统产生毒性作用。例如,MNPs通过激活NF-κB途径和NLRP3炎症小体来促进细胞凋亡,从而损害了鲤鱼鳃的免疫功能[37]。Xue等[38]用MNPs暴露斑马鱼,发现谷胱甘肽(GSH)活性在MNPs暴露5 d后显著增加,表明MNPs显著诱导了鱼鳃的氧化应激。Kim等[39]报道了MNPs会影响鱼类循环系统,影响与脂肪代谢相关的各种血液学参数,改变血液生理机能。

(2)对免疫系统的毒性作用机制。MNPs进入鱼体主要通过改变相关基因表达和改变免疫细胞因子的分泌来影响免疫系统。Limonta等[40]将成年斑马鱼已经暴露于MNPs中,通过转录组学分析发现了免疫系统基因表达的改变和脂质代谢相关的基因的下调。鱼类免疫系统的主要细胞成分是巨噬细胞、粒细胞、树突状细胞、NK细胞和T细胞[41]。鱼类免疫系统由2个主要子系统组成,先天(非特异性)和适应性(特异性)免疫系统,它们协同作用,通常是相互依存的[42-43]。Liu等[44]发现散鳞镜鲤(*Cyprinus carpio* var.)在暴露于聚氯乙烯MNPs后,肝脏中的ROS水平以及肝脏和血清中促炎细胞因子(包括*il-6*、*il-8*和*tnfα*)的蛋白质水平升高。聚苯乙烯MNPs暴露黄鳝(*Monopterus albus*)后,导致肝胰腺细胞因子基因*il-1β*和*il-8*的过表达[45]。聚苯乙烯MNPs的摄入导致鲤鱼(*Cyprinus carpio*)肠道上皮细胞凋亡,细胞因子*il-1β*、*il-6*和*tnf-α*的水平增加[46]。聚苯乙烯MNPs增加了金头鲷肠道促炎细胞因子基因表达(即*il-1β*、*il-6*和*cox-2*),并减少了*il-10*表达;此外,聚苯乙烯MNPs还诱导其他免疫相关基因的增加,如*lys*、*csf1r*和*alp*[47]。

(3)对抗氧化系统的毒性作用机制。MNPs可以使鱼类的高活性分子产生过多,氧化系统和抗氧化系统失衡,从而损害鱼类组织。Xia等[48]发现聚氯乙烯MNPs可以使鲤鱼的肝脏中的抗氧化相关基因表达的改变,超氧化物歧化酶(SOD)和过氧化氢酶

(CAT)活性呈反比关系。Rangasamy 等[49]评估斑马鱼成鱼暴露于环境相关浓度的聚乙烯 MNPs 的影响,肝脏中的 CAT 活性和谷胱甘肽硫基转移酶(GSTs)活性显著降低。聚苯乙烯 MNPs 使鲤鱼肝胰腺抗氧化酶 SOD、CAT、谷胱甘肽过氧化物酶(GSH-PX)和总抗氧化能力(T-AOC)活性降低[50]。MNPs 对鲫鱼(*Carassius auratus*)各组织血液参数、血浆成分和抗氧化剂的反应有明显影响[51]。Li 等[52]研究了 MNPs 对大黄鱼(*Larimichthys crocea*)的氧化应激,结果表明,抗氧化酶(SOD、CAT)水平在最高 MNPs 浓度下在鱼肝脏中的活性增加。Kim 等[53]用 MNPs 暴露青鳉鱼后,与对照组相比,SOD 和 CAT 的水平增加。

(4)对神经系统的毒性作用机制。粒径较小的 MNPs 可以进入到鱼类的肌肉组织和大脑等器官中,抑制乙酰胆碱酯酶活性或改变神经递质水平,从而损害鱼类的神经系统。例如,70 nm 的 MNPs 可以进入金鱼的肌肉组织中,抑制乙酰胆碱酯酶(AchE)活性[23]。斑马鱼暴露于 2 种浓度的 MNPs 中 20 d,高浓度的 MNPs 抑制了头部和身体中乙酰胆碱酯酶活性[27]。聚氯乙烯 MNPs 可以使尖齿胡鲶大脑和鳃中的乙酰胆碱酯酶活性降低[54]。七彩燕鱼(*Symphysodon aequifasciatus*)暴露于 MNPs,肠道中神经递质降低[55]。

(5)对运动系统的毒性作用机制。MNPs 在鱼类组织中的积累导致鳃盖骨的呼吸速率(ORR)增加和游泳速度降低,从而影响鱼类运动能力。MNPs 可以在尖齿胡鲶中积累,使其游泳速度显著降低[33]。摄入 MNPs 的鲈鱼表现出运动减少,在其胃肠道中发现 MNPs[56]。聚苯乙烯 MNPs 暴露斑马鱼后,主要在胃肠道积累,其次是鳃,斑马鱼在 MNPs 暴露后变得过度活跃,其游泳距离比对照组增加了 1.3 倍 ~2.4 倍[57]。金鱼暴露于 MNPs 后,MNPs 在其消化道中积累,高浓度的 MNPs 可以破坏鳃组织,增加心率,并抑制金鱼游泳速度[23]。高浓度 MNPs 暴露斑马鱼 96 h 后,发现鱼的鳃和肠道中保留了 MNPs,并观察到异常行为,如抽搐等[58]。

(6)对生殖系统的毒性作用机制。在水环境中的 MNPs 的单体和添加剂可能渗出,通过干扰下丘脑-垂体-性腺轴(HPG)而抑制性激素分泌,使得性腺发育不成熟,从而影响了生殖系统。海水青鳉暴露于环境相关浓度的 10 μm 聚苯乙烯 MNPs 60 d,延缓了雌鱼的性腺成熟,基因转录分析表明,MNPs 暴露对雌性 HPG 轴具有显著的负调控作用[12]。大于 100 $\mu g \cdot L^{-1}$ 浓度的 MNPs 使斑马鱼性腺中类固醇 mRNA 的表达产生显著变化[59]。聚苯乙烯 MNPs 可以抑制斑点叉尾鮰(*Ictalurus punctatus*)中参与性腺发育或肌肉收缩的基因的表达[60]。MNPs 使大西洋鳕鱼(*Gadus morhua*)的卵黄蛋白原 1(*vtg1*)的基因表达水平发生显著变化。这可能是 MNPs 的直接影响,也可能是 MNPs 的添加剂的内分泌干扰作用[61]。

4　MNPs 与其他污染物对鱼类的毒性效应及作用机制(Combined toxic effects and mechanisms of MNPs and other pollutants on fish)

MNPs 污染正成为全球关注的主要问题。而随着工业、农业、畜牧业的快速发展,大量的无机和有机污染物不可避免地被释放到自然环境系统中[62]。MNPs 可以吸收水生环境中的各种污染物,而被视为有害污染物的载体[63−64]。MNPs 与其他污染物潜在的协同毒性往往大于单独产生的毒性[65],MNPs 与其他污染物对鱼类的毒性效应的研究引起了人们的广泛关注。

4.1　MNPs 与水中的重金属对鱼类的毒性效应及作用机制

MNPs 与重金属结合进入鱼体中,会对鱼类组织损伤、抗氧化、免疫反应和基因表达造成的影响。MNPs 对金属离子有很强的吸附能力,两者结合形成复合污染,一方面微塑料可以与重金属形成协同作用,另一方面微塑料可以与重金属形成拮抗作用。例如,聚苯乙烯 MNPs 和铜共同暴露尼罗罗非鱼(*Oreochromis nilotica*),在鱼肝脏、肠道和鳃中表现出组织病理学改变,MNPs 增强铜在鱼肝脏中的累积[66]。MNPs 和镉可引起乌鳢氧化应激,影响抗氧化状态,CAT 活性各时间点均高于单独暴露于 MNPs 和镉[67]。MNPs 和铜会降低黑斑小鲷(*Pagellus bogaraveo*)存活率,诱导氧化应激,脂质过氧化,并对黑斑小鲷的适应性产生负面影响,在高浓度 MNPs 和铜下可能具有协同作用,在较低浓度下具有拮抗作用[68]。MNPs 和菲胁迫导致斑马鱼的氧化应激,提高免疫力和氧化应激基因的表达,而联合暴露会加剧这些变化[69]。基因表达分析在生物学研究中越来越重要,转录组分析对涉及生长、繁殖、发育、免疫、疾病、应激和毒理学的候选基因进行有效鉴定和表达分析[70−71]。例如,Liu 等[72]使用转录组学研究了 MNPs 和重金属积累对线纹海马(*Hippocampus erectus*)的影响,线纹海马体内与抗氧化途径相关的基因发生重大变化,MNPs 单独作用上调的基因数

量是 MNPs 和重金属复合作用的 2.6 倍。斑马鱼胚胎单独或组合暴露于微塑料和铜会破坏参与神经发生的基因,进而破坏细胞通路产生毒性,MNPs 可以调节铜毒性,金属毒性的增加或减轻可能取决于浓度[73]。关于 MNPs 和重金属暴露相关的神经和行为毒性作用的了解仍然很少。MNPs 与水中的重金属还可能对鱼类摄食活动[74]、游泳行为[75]和繁殖[76]有影响,但这些影响有待进一步研究。

4.2 MNPs 与水中的有机污染物对鱼类的毒性效应及作用机制

有关 MNPs 与水中的有机污染物对鱼类的毒性效应备受关注,主要集中在考察 MNPs 对鱼类早期发育阶段生理特征的影响。微塑料和持久性有机污染物(POPs)普遍存在于天然水环境中,对水生生物构成潜在威胁[77]。MNPs 与水中的有机污染物结合后,主要产生协同作用。例如,接触 MNPs 与全氟辛烷磺酸会降低青鳉胚胎存活率并阻止孵化,暴露于 MNPs 与苯并[α]芘(BaP)或二苯甲酮-3 的青鳉表现出生长减缓、发育异常和异常行为增加,与同等的水中浓度相比,BaP 和全氟辛烷磺酸添加到 MNPs 中时似乎比 BaP 和全氟辛烷磺酸单独存在于海水中时具有更强的胚胎毒性[78]。牙鲆(*Paralichthys olivaceus*)同时暴露于多氯联苯(PCBs)和 MNPs 与单独暴露于多氯联苯相比降低了鱼体长度和体质量,显著降低 L-甲状腺素和 L-三碘甲状腺原氨酸水平,甲状腺组织和鳃的形态受到更严重的破坏[79]。聚苯乙烯 MNPs 与 2,2',4,4'-四溴二苯醚共同暴露会加剧斑马鱼的形态畸变,包括心包水肿、卵黄囊水肿和尾部弯曲,与 2,2',4,4'-四溴二苯醚单独暴露相比,联合暴露导致存活率较低、体长缩短和自发运动加速[80]。斑马鱼暴露于聚乙烯 MNPs 和苯并[α]芘的畸形率显著高于单独暴露于聚乙烯 MNPs 的鱼,MNPs 表面吸附的有机污染物加剧了骨毒性[81]。

综上,MNPs 容易吸附各种环境污染物,产生复杂的二次污染物[82-83]。接触与其他污染物结合后的 MNPs 对鱼类生长、繁殖、发育、免疫等存在不利影响。

5 结论与展望(Conclusion and prospect)

本文回顾和总结了 MNPs 对鱼类毒理效应的研究进展,归纳了鱼类对 MNPs 的摄取、富集和转运规律,分析了 MNPs 的粒径作用差异,探讨了 MNPs 对鱼类的毒性效应及作用机制,并介绍了 MNPs 与其他污染物对鱼类的毒性效应。尽管目前关于 MNPs 对鱼类毒性效应及机制研究取得了积极的进展,但仍需对以下问题进一步深入研究。

(1)现有关于 MNPs 对鱼类毒性效应及机制的研究,多选用单一的种类和形状的 MNPs。而环境中存在的不同形状和种类 MNPs 对鱼类毒性效应及机制研究十分缺乏;

(2)在 MNPs 对鱼类毒性效应的研究中,MNPs 对鱼类的暴露时间不长,需要加强 MNPs 长期暴露对鱼类产生的毒性效应的研究;

(3)研究中采用的鱼类单一,关于 MNPs 在食物链各级生物中的毒性效应及机制的研究十分欠缺。应加强关注 MNPs 在食物链各级生物中的毒性变化,探讨其引发的毒性机制。

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