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微塑料对双壳贝类毒性效应的研究进展

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摘　要

微塑料因比表面积大、传输距离长、吸附性强、难降解等特性而广泛存在于水环境系统中，其造成的污染问题已经引起了世界各地学者的广泛关注。本文以双壳贝类为主要对象，综述了微塑料对水生生物造成影响的途径和海洋中微塑料引起双壳贝类产生的各种毒性效应。今后，应进一步加强微塑料对双壳贝类毒性效应的研究，建立以双壳贝类作为水环境中微塑料污染的指示生物，形成一套系统的微塑料生物监测方法。

关键词

微塑料，水生生物，双壳贝类，毒性效应

Research Progress in the Study of Microplastics on Toxic Effects on Bivalve Mollusks

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Abstract

Microplastics are widely present in the water environment system because of their large specific surface area, long transport distance, strong adsorption, and difficulty in degradation. The pollution problems caused by them have attracted extensive attention from scholars all over the world. In this paper, bivalve shellfish as the main object, the influence of microplastics on aquatic organ-

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isms and various toxic effects caused by microplastics in Marine bivalve shellfish were reviewed. In the future, the toxic effects of microplastics on bivalves should be further studied, and bivalves should be used as indicators of microplastic pollution in water environment, so as to form a set of systematic biological monitoring methods for microplastics.

Keywords

Microplastics, Aquatic Organisms, Bivalve, Toxic Effect

1. 引言

塑料因可塑性强和化学稳定性高等特点，被广泛应用于服装、包装、电子等各类产品中[1]。根据报道，2019 年全球塑料年产量已远远超过 3 亿吨，中国作为生产大国，产量更是达到了总产量的 31% (如图 1 所示)。根据预估，2050 年塑料总产量将增加 330 亿 t [2]。虽然塑料的污染已经引起众多关注，但仍存在约 80%的塑料产品流入到垃圾填埋场和自然环境中，引发严重的环境污染问题[3]。

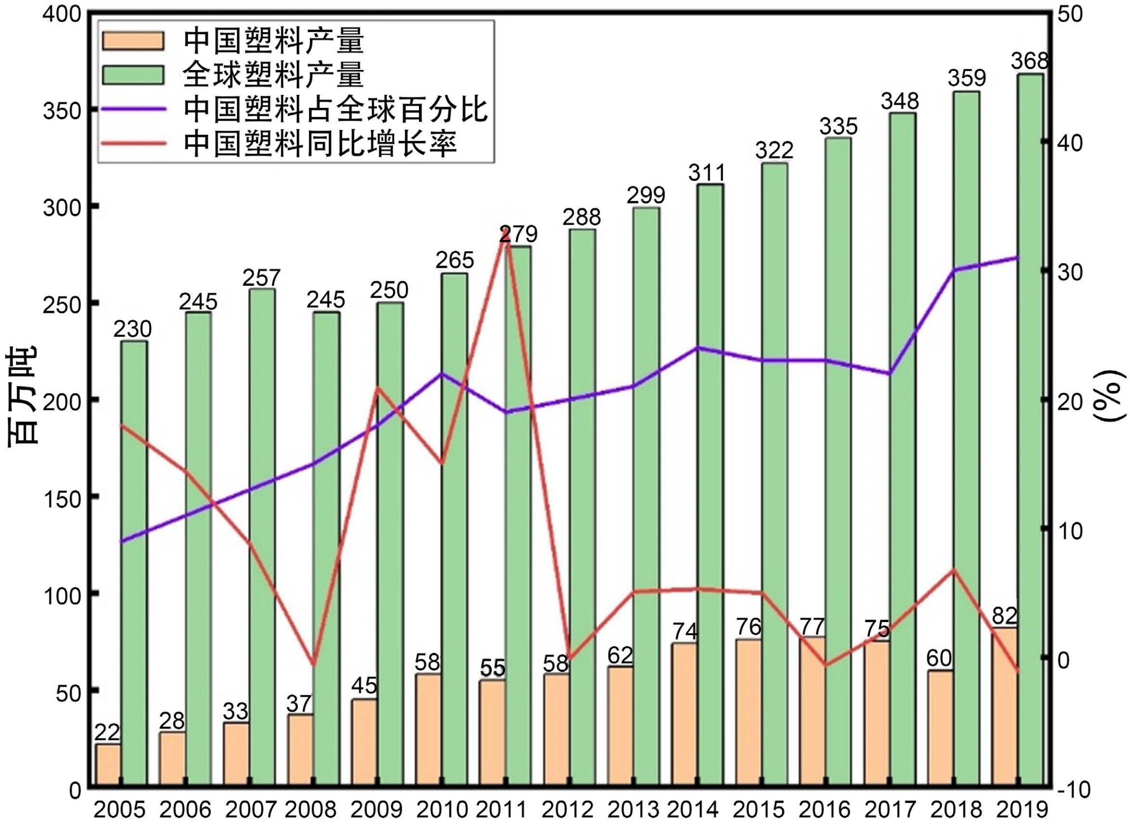

Figure 1. Global and Chinese plastics production and growth rate, data from “National Bureau of Statistics” and “Plastics Europe”
图 1. 全球和中国塑料产量及增速，数据来源于“国家统计局”和“Plastics Europe”

微塑料主要分为原生微塑料和次生微塑料。原生微塑料指直接释放到环境中且粒径 < 5 mm 的颗粒，如纺织品[4]和化妆品[5]等；次生微塑料指较大的塑料碎片，如废弃的塑料袋[6]、渔网[7]等在自然和人为作用下分解形成的。微塑料具有粒径小、数量多、吸附性强和传输距离长等特点，极易对生态环境和人体健康造成危害，从而引起了国内外学者的广泛关注[8]。

据研究表明，微塑料已经广泛存在于大气[9]、土壤[10]、海洋[11]、湖泊[12]、沉积物[13]以及生物体内[14]。而微塑料对生物体产生毒害作用的途径大致可以分为三类，一方面微塑料易被水生生物误食形成假的饱腹感，并有可能随着食物链传递到更高的营养级生物；另一方面，塑料在生产过程中参杂的添加剂会伴随着降解解析出来；最后，其可以吸附水中存在的有机污染物和重金属等，从而影响水生生物的生长繁殖。而影响这些途径的因素不仅仅是塑料的固有属性(核心组成、表面电荷、大小、形状、功能等)，接受介质的属性(pH、离子强度、天然有机物)也会影响微塑料在不同环境下的团聚、聚集和沉降，进而影响生物利用度、吸收和毒性[15]。

贻贝作为典型的滤食性双壳贝类，被广泛应用于全球海洋污染的生物监测中，不仅提供生境异质性，减少因其悬浮饲养特性而导致的水体浑浊，封存氮，为更高的营养水平提供食物，更能支持全球水产养殖业[16]。贻贝之所以被广泛用作生物监测物种的原因有以下几个：首先，贻贝对溶解氧、温度、盐度和食物供给等环境因子具有较广的耐受范围[17]；其次，贻贝坚硬的外壳和处理简单等特征极大地减少了实验过程中的程序性污染[18]；最后，贻贝是广泛应用于与微塑料相关研究的海洋无脊椎动物，不仅摄取天然的微塑料[19]也摄取实验室制备的[20]。随着各项研究的进行，不良毒性效应也随之报道，包括降低过滤效率、足丝产量、生长繁殖、亚致死效应和炎症免疫反应等[21]。然而，微塑料对这些滤食性动物的真正影响仍然缺乏了解，因为大多数研究采用的方法不能准确反映动物在自然环境中发生的条件。

1.1. 微塑料对水生生物影响途径

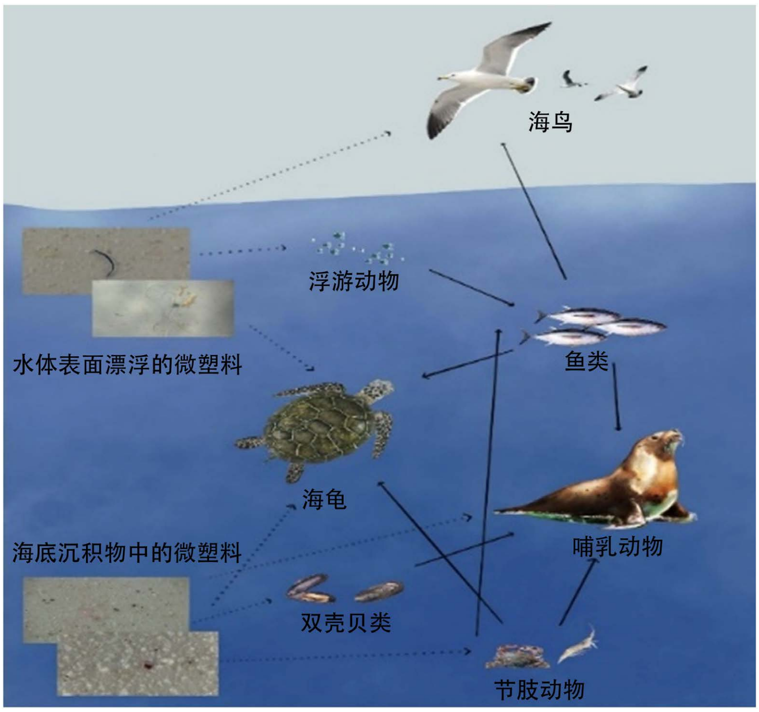

Figure 2. Biological uptake and food chain transfer of microplastics
图 2. 微塑料的生物摄入及食物链传递

如图 2 所示，微塑料进入水体环境后，因其形状、大小和颜色与水生动物的食物相似，容易引起水生动物的误食；其次，微塑料本身含有单体化合物和塑料添加剂等有毒有害物质，伴随其降解不断向外界释放；最后，微塑料可以作为微生物、有机污染物和重金属等的载体，在被水生动物误食后，对其生长繁殖造成有害影响。

1.2. 微塑料被水生生物误食

由于微塑料大小、形状和颜色与普通的水生生物的食物相似，导致水生生物在摄食的过程中可能会将微塑料摄入体内[22]，造成生物机体损伤、堵塞食道并产生假的饱腹感，进一步引起生物摄食率降低、能量匮乏、功能受损甚至死亡。

研究表明，微塑料在浮游动物[23]、动物胚胎或幼体[24]、贝类[25]、和鱼类[26]等生物体中广泛存在，甚至在人类婴儿胎盘中也发现了微塑料的存在[27]。Carpenter 等[28]发现在不同阶段鱼体内存在塑料颗粒。除此之外，在以浮游生物为食的中层鱼类胃含物中发现微塑料含量高达 35%。而处于低营养级的浮游动物，由于其对食物的辨别能力较差，很难区分微塑料和食物的差异，再加上一些低密度微塑料在表层聚集，致使浮游动物极易受到影响。在对葡萄牙沿海区域 152 个浮游样本的调查过程中发现，其中 93 个样本中检测出了微塑料的存在，占总样本的 61% [29]。

底栖生物中贻贝作为积累微塑料的主要水生生物之一，已经在世界多个区域得到贻贝体内存在微塑料的证明。Gedik 等[30]对土耳其黑海、马尔马拉海和爱情海沿岸的 23 个不同点位收集的贻贝进行微塑料污染的分析，发现 48%的贻贝样本中含有微塑料，其中 PET、PP 和 PE 分别占总微塑料的 32.9%、28.4%和 19.4%。此外，对来自中国沿海 6 个地点的 100 只贻贝进行测试，发现每千克组织中平均含有 0.58 mg 塑料(范围为 0.16~1.71 mg/kg)，其中聚乙烯是测量到的最丰富的塑料类型[31]。

除了对环境中的野生贝类进行了检测之外，Cho 等[32]对韩国三个主要城市的渔业市场销售的双壳贝类进行了市场调查，以牡蛎、贻贝、马尼拉蛤和扇贝 4 种常用的双壳动物作为检测物种，其微塑料的平均浓度分别为 0.15 ± 0.20 n/g 和 0.97 ± 0.74 n/individual，并且根据不同的培养方法和生境特征，可以观察到不同的聚合物组成。

1.3. 微塑料降解老化过程中释放有毒物质

塑料在生产的过程中会使用多种添加剂，如塑化剂和表面活性剂等。塑料中的这些添加剂在经过在老化过程中很容易浸出，在迁移的过程中，会使其破碎并出现裂纹[33]；其次，塑料聚合物在氧化剂和紫外光的作用下，易发生断链从而产生一些含氧官能团[34]；并且环境中的微塑料通过吸附会在表面形成生物膜，附着的生物在代谢的过程中释放胞外酶，促使聚合物断链[35]。

从现有研究可以看出，海洋环境中的塑料颗粒中均有塑化剂的存在[36]。同时，添加剂与其它物质的结合，会改变塑料的浸出能力和潜在毒性[37]。这些结合物能够渗透进入动物的细胞膜，从而参与生化反应和诱导毒性效应[38]。但植物细胞的细胞壁使这些效应在植物细胞中表现不明显。

1.4. 微塑料作为有毒有害物质的载体

水生环境中的微塑料还可以吸附在其表面的化学污染物和微生物等。并且老化后的微塑料物理化学性质的改变，导致其具有较大比表面积和更多的附着位点，在水环境中能够吸附有机污染物和重金属等，如滴滴涕[39]、多氯联苯[40]、多环芳烃[41]和重金属[42]等。

Gunasekaran 等[43]研究了低浓度和纳米氧化锌颗粒联合微塑料在 3 种暴露浓度下对盐生杜氏藻的毒性。研究发现，在普通 PS 微塑料的存在下，块状和纳米 ZnO 颗粒的有害影响显著降低。此外，微塑料

还可以吸附细菌，获得营养物质。通过分析海洋表层的风化微塑料碎片的生物群落结构，研究人员发现了自养生物、异养生物和共生菌的存在[44]。

2. 微塑料对双壳贝类的毒性效应

微塑料会与水体中的生物和非生物发生相互作用形成密度较大的团聚体，最终坠入沉积物中。有研究表明，沉积物是大部分微塑料的最终归宿[45]。本文以底栖生物中的典型生物——双壳贝类作为研究对象，综述微塑料对双壳贝类产生的危害。

目前大多数关于双壳贝类摄入微塑料的研究都是在实验室内模拟的，主要研究微塑料对滤食、生长发育、繁殖、死亡率、足丝产量和氧化应激反应的影响。在野外对微塑料的生物效应研究较少，主要原因是难以控制或实时监测饲养等多种环境变量[46]。

从表 1 和表 2 可以看出，实验条件下微塑料的尺寸都在几微米甚至纳米级别，暴露剂量也处于一个较高的程度，此外对于微塑料的类型也比较单一。相对于实验条件，野生条件下的微塑料研究有了很大的区别。首先，在微塑料上，从野生条件下的双壳贝类体内提取的微塑料尺寸最大可以达到几十毫米；其次，在暴露剂量上，可以推测海洋环境中微塑料浓度要低于实验条件下；而在微塑料类型上，野生条件下检测出的微塑料种类更为丰富，这可能会对双壳贝类毒性机理的研究增加困难。这更加说明野生条件下双壳贝类的研究亟待加强。

Table 1. Microplastic feeding by bivalve shellfish under experimental conditions
表 1. 实验条件下双壳贝类摄食微塑料的研究

种类	微塑料微粒尺寸	暴露剂量	类型	分子式	主要研究成果	参考文献
贻贝	50 nm	0.1, 0.5, 1, 5 mg/L	聚苯乙烯(PS)	$(C_8H_8)_n$	NPs 会破坏细胞的内部组织，干扰参与能量代谢的酶的正常结合	[47]
牡蛎	4~6, 11~13, 20~25 μm	0.1, 1, 10 mg/L	高密度聚乙烯(HDPE)		粒径较小的 MPs 更容易诱发畸形和发育停滞	[48]
珍珠牡蛎	6 μm, 10 μm	0.25, 2.5, 25 g/L	聚苯乙烯(PS)	$(C_8H_8)_n$	PS 影响了珍珠牡蛎的同化效率和能量平衡，并对其繁殖产生负面影响	[26]
白斑贻贝	10~45 μm	0.0 ~ 0.8 g/L	高密度聚乙烯(HDPE)		MPs 可以通过降低滤食性生物的滤过率来影响摄食	[49]
蓝贻贝	100 nm, 2 μm	0.42, 28.2, 282 μg/L	聚苯乙烯(PS)	$(C_8H_8)_n$	在较高的浓度和较长的曝光时间下畸形更明显	[50]

Table 2. Microplastic ingestion by bivalves under wild conditions
表 2. 野生条件下双壳贝类摄食微塑料的研究

采样点	样品数量(个)	检出率	主要类型	形状	丰度(n/个)	粒径	参考文献
Ontario, Canada	21	71%	PP, PE, PS, nylon	颗粒、碎片、纤维	0~7	21~298 um	[51]
New Zealand	54	66%	PE, PA, PAI, PVC, rayon, nylon,	碎片、纤维、微珠	0~1.5	50~700 um	[52]
England	269	88.5%	PS, PE, PP	纤维、碎片、微珠	1.43~7.64	-	[53]
Cape Town	168	98%		纤维、碎片、球体	2.33 ± 0.2	50~1000 um	[54]

Continued

Cape Town	-	-	PET, PVC, nylon	纤维、碎片、发泡、颗粒、薄膜	3.8	≤2000 um	[55]
Scotland	-	-	PET, PEU	纤维、薄膜、球体	3.2 ± 0.52~ 3.5 ± 1.29	-	[56]
Adriatic Sea	360	-	PE, PP, PET, PS, PLY, PVC	颗粒、纤维、碎片		20~40 um	[57]
Le portel; Baie des Veys; Baie d, Authie	200	45%	-	纤维、颗粒	0.76 ± 0.40~ 2.46 ± 1.16	27.3 ± 0.5~ 47.9 ± 1.5 mm	[58]
U.K.	162	-	PP, PET, PE, rayon,	纤维、碎片、球体	1.1~6.4	8~4700 um	[59]

2.1. 滤食

贻贝以滤食模式为主，直接曝露于水体中[60]，水中的颗粒物通过鳃产生的电流进入口中，到达食道。其中一些有机颗粒被摄入，其余的留在粘液当中并转化为假粪便被清除。然而，当颗粒浓度很高时，贻贝可能会失去选择能力，意外的摄入无机成分[61]。贻贝可以反映生活环境的质量，因此通常被用作监测项目中的指示生物[16]。

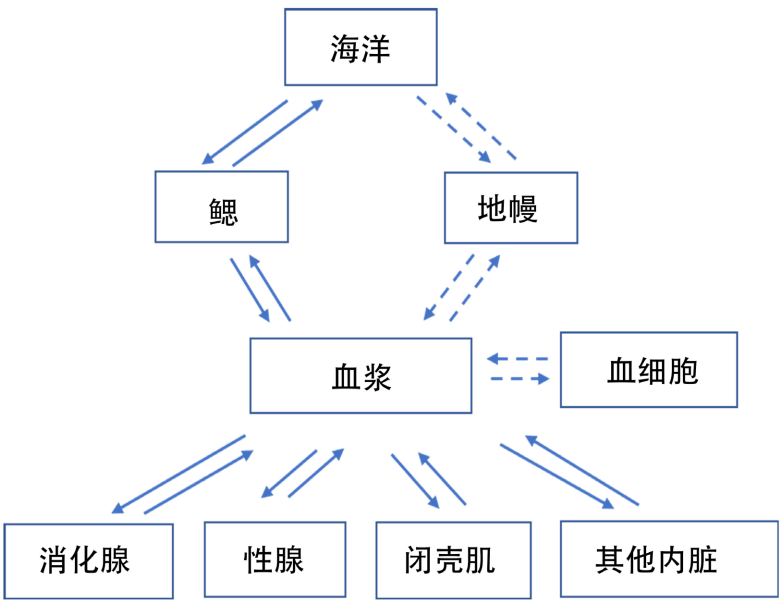

Figure 3. Schematic diagram of the main pathways for transport and distribution of contaminants within bivalves. Solid and bold lines indicate the main pathways, and dashed lines and arrows indicate other pathways. Adapted from Ricciardi [65]
图 3. 污染物在双壳贝类内部运输、分布的主要途径示意图。实线和粗体表示主要途径，虚线和箭头表示其他路径。改编自 Ricciardi [65]

贻贝以浮游植物作为主要的食物来源，又因浮游植物的大小与微塑料相似而成为贻贝研究的侧重点。Christoforou 等[62]将蓝色贻贝长期曝露与 100 μm 的微纤维中发现，贻贝在曝露 39 天后对浮游植物的清除能力降低了 21%，并推测是由于微纤维在消化系统中积累造成的。但并不能因此而夸大微塑料的毒性作用。相反，微塑料对滤食性动物的影响可能与天然悬浮体(红粘土)的影响相似[63]，甚至在某一方面会

降低有毒有害物质对生物的影响。在较短的曝露时间内，其滤食效率仍处于较高水平。有研究表明，在微塑料处于较高浓度下，贻贝清除微塑料的程度和相同大小的食物(微藻)相同，且经过 6 天的净化，大约有 85%的微塑料被清除[64]。如图 3 所示，海洋中的污染物大部分被双壳贝类的鳃摄食后进入血浆中，少部分到地幔中也会进入双壳贝类的血浆中。血浆中的污染物随后进入消化腺、性腺、闭壳肌和其他内脏中，有少部分进入到血细胞中，从而对双壳贝类产生毒性效应。

2.2. 生长发育

双壳贝类长期曝露于微塑料中会产生假粪便，从而消耗能量。对于早期的幼虫阶段，这可能会对其生长和成年期的持续发展产生不利影响。例如，Tallec 等[66]通过研究不同尺寸和功能的聚苯乙烯对太平洋牡蛎的三个关键繁殖步骤(受精、胚胎发育和变态)的毒性程度发现，PS-NH_2 在牡蛎受精卵膜表面的吸附显著降低了孵化成功率和胚胎发育，纳米塑料造成了受精成功和胚胎幼虫发育的显著下降，出现许多畸形，直至发育完全停滞。在此基础上，通过评价羧基化(PS-COOH)和氨基化(PS-NH_2)聚苯乙烯微塑料对 3 个关键生命阶段的发育中的蚌幼虫(受精卵、D-veliger 幼虫和 umbo 幼虫)的毒性反应，显著降低了蛤蜊的孵化率[67]。

由此看出，尽管双壳贝类的滤食能力对微塑料的影响有很大的抑制作用，但在长时间的曝露下依旧会对双壳贝类的生长发育产生的一定的影响。

2.3. 死亡率

双壳贝类的死亡率与其生存环境中微塑料的大小和形状息息相关。有研究表明，颗粒的大小会影响亚致死毒性，纳米塑料相比于微塑料更容易穿透组织和血淋巴，从而增加了吞噬细胞的比例(表明免疫反应增强)，并导致微核的形成显著增加。

此外，微塑料中具有高长宽比的微纤维比球形微珠有更大的可能性聚集并残留在消化道内，增加其亚致死的概率。Rist 等[68]在 91 天的曝露中，逐渐增加聚氯乙烯颗粒的含量，发现平均生存时间随着聚氯乙烯颗粒的增加而明显降低，在聚氯乙烯 2160 mg/L 的两组中，即有和没有荧光蒽污染的两组中，动物的存活时间只有对照组的一半。

2.4. 氧化应激反应

氧化应激是由于机体抗氧化系统和活性氧等促氧剂之间的不平衡产生的。这种不平衡会影响生物体的发育、繁殖和寿命[69]。研究表明，贻贝暴露在含有微塑料球的水体中，引起血细胞中活性氧的产量增加，同时贻贝组织中抗氧化剂和谷胱甘肽相关酶增强，其亚细胞氧化应激通道被激活[70]。

Magara 等[71]通过观测贻贝体内过氧化氢酶和谷胱甘肽过氧化氢酶值的提高，得出仅微塑料暴露就对其氧化应激系统产生了直接影响。在贻贝的暴露实验中发现，微塑料聚羟基丁酸和聚乙烯会导致贻贝鳃中过氧化氢酶和谷胱甘肽 S-转移酶、消化腺中超氧化物歧化酶以及两个组织中的硒谷胱甘肽过氧化物酶的活性水平降低。

3. 总结与展望

微塑料在自然环境中分布广泛，并且由于其自身的性质，可能造成潜在的生态风险，因此引起了人们的高度关注。近年来，针对海洋生物体内微塑料的污染问题以及其产生毒性机理的研究也在不断深入。本文从多个方面总结了水环境中的微塑料对水生生物所造成的影响，并且着重阐述对各种双壳贝类可能产生的毒性效应。

今后，应进一步加强微塑料对双壳贝类毒性效应的研究。加强野生环境中微塑料对双壳贝类污染问

题的研究，做出更全面精准的生态风险评估。建立以双壳贝类作为水环境中微塑料污染的指示生物，形成一套系统的微塑料生物监测标准方法。

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