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滩涂底栖动物有机污染生态学研究进展

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摘要:底栖动物由于对有机污染物具有较强的吸收能力,再加上其移动能力较差、生活方式比较固定,而被广泛运用于滩涂有机污染的研究。目前这些研究主要集中在如下几个方面:(1)有机污染物在底栖动物体内的分布特征及在底栖食物链中的动力学研究;(2)底栖动物对有机污染物的生理响应研究;(3)污染物对底栖动物群落组成和结构影响研究;(4)底栖动物在滩涂有机污染检测中的应用研究。研究结果表明:滩涂底栖动物对有机污染物的累积具有选择性和季节波动性;有机污染物可以在底栖食物链中传递;底栖动物体内的有机污染物成分和含量可以有效地指示其生存环境的有机污染状况;底栖动物的混合功能氧化酶和抗氧化酶系统对体内有机污染物的累积产生积极的响应;有机污染物对底栖动物的免疫系统造成不利影响,并对遗传物质造成破坏;有机污染对底栖动物的群落组成和结构具有显著的影响。

关键词:底栖动物;有机污染;PAHs;PCBs;OCPs;石油烃

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The research progress of organic pollutants ecology on the benthic organisms

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Abstract: Following the development of industry, many organic compounds have been discharged into the aquatic environment, resulting in serious pollution on the beaches. Many of these pollutants, such as PAHs, PCBs, OCPs and petroleum hydrocarbon, have been proved to be harmful to the human population. The benthic organisms, based on their ability in bio-accumulating organic contaminations, have been used internationally for bio-monitoring organic pollution in the coastal environment. In this paper we summarize the recent studies of benthic organisms in organic pollution ecology being mainly the following aspects: (1) The determination of the concentration of organic pollutants in benthic organisms and the bioaccumulation kinetics that organic pollutants accumulate and distribute in benthic fauna; (2) The physiological response of benthic organisms to the organic pollutants; (3) The effects of organic pollutants on the benthic fauna community. Studies here show that benthic organisms exhibit different accumulation patterns according to the source of pollution they were exposed to. Benthic organisms are observed to display a yearly cycle in the uptake of contaminants, due to changes associated with their reproductive cycle and lipid content. Organic pollutants are found to be harmful to the immune system of benthic organisms and cause an increase in DNA damage. These studies also show that the persistence of organic pollutants has a negative effect on the benthic community. In this paper, research progress in this field is reviewed and future research is suggested.

Key words: benthic organism; organic pollution; PAHs; PCBs; OCPs; petroleum hydrocarbon

随着河流两岸和沿海工农业的急速发展,加上船舶运输和渔业等人为活动的影响,大量化学污染物被排放到江河湖海之中,其中包括多种有机污染物。在各种主要有机污染物中,已知多环芳烃(PAHs)、多氯联苯

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(PCBs)、有机氯杀虫剂(OCPs)和石油烃类等有机物均可以在海洋生物脂肪中积累[1~3]。已有研究表明人工合成有机物在水生动物体内的积累高于周围海水含量的1000倍以上[4]。虽然还没有证据表明所有的有机污染物都对动物体产生毒性,但是很多研究证明有机污染物的潜在危害是相当大的。例如,PAHs、PCBs等物质具有"三致"作用[5~7],PCBs和OCPs等具有环境激素作用,能够导致生物体内分泌紊乱、生殖及免疫系统失调[8~10]。特别是,这类污染物可以在动物组织中存留相当长的时间,对这些水产品的消费在某种程度上构成潜在的危险性。

虽然有机污染物在国际上已经被禁用多年[11],但由于其持久性和抗生物降解性,在环境样品中仍能检测出较高的含量[8,12]。滩涂处在水体与陆地的交错过渡带,同时受到众多污染源的污染,是沿海陆源污染物和海上排污的主要受纳场所。同时,作为重要的后备土地资源,滩涂对渔业和水产养殖业来说显得极为重要。因此,滩涂痕量有机污染物的研究显得尤其重要。

由于滩涂有机污染研究的重要性,在过去的几十年时间里,这一研究领域一直是污染生态学研究的热点。由于滩涂底栖动物有如下优点:(1)生物量丰富;(2)物种多样性丰富;(3)分布广泛,适应不同生境;(4)移动力相对较低;(5)生活周期多样性丰富(从最短的6d到最长的超过2a);(6)直接与空隙水和沉积物中的污染物进行交互作用[13],在过去的几十年,许多污染生态学家都倾向于用底栖动物来监测滩涂环境。

目前,底栖动物的有机污染生态学研究主要集中在以下几个方向:(1)有机污染物在底栖动物体内的分布特征及在底栖食物链中的动力学研究;(2)底栖动物对有机污染物的生理响应研究;(3)有机污染物对底栖动物群落的影响研究;(4)底栖动物在滩涂生态系统中的有机污染监测应用。

1　有机污染物在底栖动物体内的分布特征

环境中的有机污染物种类繁多,常见的有多环芳烃(PAHs)、多氯联苯(PCBs)、有机氯农药(OCPs)和石油烃类等。由于有机污染物大都具有水溶性低、蒸汽压低、表面亲和力大等特性,因此极易被吸附在悬浮颗粒物上,随水流和气体迁移进入河流和海洋,在沉积物中可以被高度富集。

滩涂底栖动物较固定地生活在滩涂的沉积物中,直接以沉积物中的有机颗粒为食,或者靠过滤水中悬浮的有机质颗粒为食,或者从饵料中吸收有机污染物,也可因暴露在含有机物的环境中从体表或者呼吸器官通过扩散作用吸收污染物[1,14,15],因此可在体内富集大量的有机污染物。从目前的资料看,对滩涂底栖动物的有机污染研究最多的就是污染物的分布特征和动力学的研究。研究对象集中在四大类:PAHs、PCBs、OCPs和石油烃类。

1.1　PAHs

多环芳烃(polycyclic aromatic hydrocarbons, PAHs)是在海洋滩涂生态系统常见的有机污染物。PAHs由多个苯环构成。由于具有疏水性的特点,在水生生态系统中PAHs通常趋向于分配到土壤或沉积物颗粒上,很少保留在水相中。底栖动物由于直接取食沉积物颗粒而造成对PAHs的积累[16]。

Nas等[17]比较了不同的滨海滩涂指示生物(*Mytilus edulis*, *Modiolus modiolus*, *Littorina littorea* 和 *Patella vulgata*)对不同成分PAHs的累积情况,同时与沉积物的PAHs组成和含量进行比较。该研究的生物样品的采集经历20余年,样地覆盖受7个冶炼厂影响的海湾。研究结果表明:(1)这些指示生物较好的反映了周围环境的污染状况;(2)而且在一定程度上反映了污染物的来源;(3)指示生物累积的PAHs成分与沉积物中的相似;(4)不同生物累积的主要PAHs成分不同。有研究表明,不同种类的底栖动物对PAHs均有不同程度的累积,而且这种累积与底栖动物在食物链中所处的位置有关[14,18]。Brunson等[19]和Hyotylainen等[20]的研究则进一步指出,在底栖动物中,PAHs的生物-沉积物富集因子(biota-sediment-accumulation factors, BSAFs)在1.0~5.7之间,与理论上的BSAF值1.7接近。这些研究结果表明,不同种类的滩涂底栖动物对PAHs都有一定程度的累积,而且对PAHs的累积量具有种间差异性,而这种差异性与底栖动物在食物链中所处的位置有关。

实际上,不同底栖动物对PAHs的累积除了在量上的差别以外,对不同成分PAHs的吸收也是具有选择性的。McIntosh等[21]与Roper等[22]的研究显示,暴露在PAHs污染条件下,贻贝(*Mytilus edulis*)体内检测到的

PAHs物质主要是茨蒽等分子结构具有5环的PAHs。Narbonne等[23]的研究发现，底栖动物 *Corbicula fluminea* 对PAHs的吸收除了具有选择性，还存在时间差异性。研究发现 *Corbicula fluminea* 在最初的24h里吸收PAHs的速度是很快的，而且主要吸收低分子量的PAHs。暴露1d后，对蒽和菲的吸收速度有明显的下降，2d后对芘的吸收速度也明显下降，两周以后对苯并[a]芘(B[a]P)的吸收速度下降(但在这时候累积的B[a]P浓度已经比其他PAHs类物质的含量高了)。

许多研究表明，底栖动物对PAHs的吸收与季节的变化也有密切的联系。Miles等[24]测定了不同季节滩涂蓝色贻贝(*Mytilus* spp.)和螃蟹(*Hemigrapsus* sp.)的PAHs含量。结果表明PAHs的生物累积量在雨季明显变大，Miles等人认为这是因为雨季水将更多的PAHs从陆地携带到海湾的缘故。在Webster等[25]、Piccardo等[26]和Maruya等[27]的研究中也观察到了包括贻贝(*Mytilus edulis*)在内的不同底栖动物对PAHs吸收的季节波动。对于沙蠋属的 *Arenicola marina* 来说，这种对PAHs吸收的季节波动似乎与其生殖活动有关。Kaag等[28]观察到 *Arenicola marina* 体内的PAHs在产卵期前含量最高，而产卵期间PAHs水平显著下降。但是进一步的研究却没有发现生殖腺发育完善与否和样品体内的PAHs含量有直接联系。

从上述文献中可以看出，不同种类的滩涂底栖动物都能够对PAHs有一定程度的累积。这种累积具有选择性：不同物种累积的数量不一样，对不同成分的PAHs累积量也不一样。值得注意的是这种累积有着明显的季节波动性，而且似乎受到生殖行为的影响，值得进一步的深入研究。

1.2 PCBs

多氯联苯(polychlorinated biphenyls, PCBs)是的具有类雌性激素作用的一类持久性的有机污染物。由于多氯联苯的理化性质稳定，难以降解(其半衰期长达40a左右)，加上其长期积累以及具有亲脂性的特点，在不同种类的动物体内都有大量富集。关于PCBs在大型水生动物体内的动力学和生理学的研究(例如含量分布、食物链的传递、生长率、生殖影响等)已有很多[29~33]，在底栖动物中的研究也有不少，主要集中于含量测定方面。

Kim等[34]的研究显示，靠近污染源的贻贝样品体内的多氯联苯(PCBs)含量较高。Liang等[35]对香港米埔基围塘红树林区的PCBs污染生态风险进行评价时，测定了日本沼虾(*Macrobrachium nipponese*)、刀额新对虾(*Metapenaeus ensis*)体内脂质百分含量和脂质内PCBs含量，发现两者正相关，而PCBs含量与体重无关。Pastor[36]和Fairey[37]等在他们的实验中也曾得出过相同的结论：生物体内脂质中PCBs的含量是由生物体内脂质百分含量决定而非生物体的体重决定的。研究表明，PCBs在水体、沉积物和生物体三者之间有明显的富集和放大作用[38]，但是由于底栖动物食性的特殊性以及底栖食物链的复杂性，PCBs在不同底栖动物中的累积量存在着比较大的差异[14,39]。由于对食物的吸收机制不同，底栖动物间对不同类型PCBs的累积量也存在着明显的差异[40,41]。这些特点对于筛选滩涂环境PCBs污染的指示生物是非常有用的。从目前的研究结果也可以看出，由于具有亲脂性的特点，PCBs倾向于通过食物链向高级营养级传递。研究PCBs在底栖动物体内的累积分布和在水生食物链中的传递，对于进一步了解高级营养级PCBs的来源，以及PCBs的环境行为具有十分重要的意义。

1.3 OCPs

有机氯杀虫剂(organochlorine pesticides, OCPs)如DDT、HCH等均是环境中典型性的持久性有机污染物，由于其具有毒性大、难降解、易于在生物体内富集等特性，其环境行为一直是污染生态学的研究热点。有机氯杀虫剂虽然被禁用了多年，但由于这类农药的高化学稳定性，并没有在环境中消失，仍然可以在土壤、水体和沉积物中大量检测出[42~46]。底栖动物由于对这类污染物有较强的吸收能力，再加上其移动能力较差、生活方式比较固定，而成为有机氯杀虫剂污染监测较为理想的指示生物。

有报道指出，在土壤沉积物中的有机氯污染物浓度低于检测限的情况下，仍可以在贻贝(*Mytilus edulis*)体内检测到较高含量的有机氯成分[47]。Berge[48]等的研究表明，螃蟹(*Cancer pagurus*)在体内累积的有机氯污染物含量可以达到土壤沉积物中含量的100倍以上。对双壳类软体动物的研究表明，一些种类软体动物软组织中有机氯杀虫剂的含量可以有效地反映出环境中污染物的水平[49,50]。另外一些研究表明，由于亲脂的特性，

底栖动物体内的有机氯杀虫剂主要累积在脂质中[51,52]。

1.4 石油烃类

由于油船泄漏、船舶运输、机动车不完全燃烧尾气的沉降作用等原因,石油烃类有机物也是滩涂环境的主要污染物[53,54]。底栖动物除了可以通过直接取食沉积物颗粒而累积吸附于颗粒上的有机污染物以外,还可以直接从水体或者沉积物空隙水中吸收石油烃类污染物的水溶性成分[55]。

研究表明,贻贝等底栖动物对石油烃类污染物的累积非常明显[56,57]。不同种类的海洋动物对石油烃类物质的累积程度差异很大,一般呈双壳类 > 头足类 > 甲壳类 > 鱼类的趋势[58,59]。另外,底栖动物对石油烃类污染物的累积也和季节变化有关。Lavarias 等[60]用轻质原油的水溶性成分(WSF)对处在不同生活史阶段的对虾(*Macrobrachium borellii*)进行毒性试验,发现对虾生活史早期不易受到 WSF 毒性的影响,而成体吸收和排除 WSF 的速度很快。Hellou 等[61]研究了海岸潮间带排污管附近的贻贝有机污染物累积量与污水中溶解态有机污染物的关系,发现在春季污水中汽油、柴油等石油烃类污染物含量增加的同时,它们在贻贝体内的累积量也相应增加了。石油烃类污染物对底栖动物的影响比较复杂,有待于进一步的研究。

2 底栖动物对有机污染物的生理响应

由于环境中的有机污染物的对生物体的作用是非常复杂的,除了进行化学分析以外,人们运用生物体内的各种生理生化指标来评价有机污染物对生物体的影响。目前,底栖动物对有机污染的生理响应研究主要集中在酶系统、免疫系统和遗传毒性等方面。

2.1 酶系统

暴露在污染条件下,生物体一般倾向于将污染物直接降解,以使自身的细胞损伤最小化。这种自身保护机制一般涉及到混合功能氧化酶系统(Mixed-Function Oxidase,MFO)和抗氧化酶系统(Antioxidant Enzymes)活性的改变。混合功能氧化酶系统存在于所有的脊椎动物和大部分无脊椎动物中,其作用是代谢非极性的亲脂性有机化合物,包括各种内源性的和外源性物质。抗氧化酶系统的作用是清除体内过多的氧自由基,保护躯体免受氧自由基的毒害。根据这一原理将可将这些酶系统作为生物标记物进行有机污染监测的。

研究发现,有机污染条件下,底栖动物的 MFO 和抗氧化酶系统活性存在季节性的波动,这种波动除了和底栖动物体内有机污染物的季节波动有关之外,还受到生殖腺成熟、食物成分的改变、水文条件变化等因素的影响[62~64]。

虽然有机污染物对 MFO 和抗氧化酶系统的活性均有显著的影响,但是不同类型的有机污染物对酶的影响是具有针对性的。Gowlanda 等[65]的研究发现,PAHs 中只有 5~6 环的分子对贻贝(*Mytilus edulis*)肝胰腺谷光甘肽 S-转移酶(GST)的活性有影响。Cheung 等[66]的研究发现,贻贝(*Perna viridis*)腮的超氧化物歧化酶(SOD),NADPH DT-硫辛酰胺脱氢酶(DT-d)和脂质过氧化反应与组织中苯并[a]芘(B[a]P)和 PAHs 等有机污染物的含量无关;贻贝体内的主要抗氧化参数是由组织中污染物的增加诱导的;在所有的抗氧化参数中,谷光甘肽(GSH)的活性与有机污染物含量的关系最密切。

另外,王淑红等[67]和冯涛等[68]的研究还发现,PAHs 类污染物对底栖动物超氧化物歧化酶(SOD)活性的影响随着污染物浓度和作用时间呈动态变化趋势。

由已知的研究结果可以看出,底栖动物混合功能氧化酶系统和抗氧化酶系统的酶类都能对有机污染物产生应激反应,一些酶的活性与污染物的含量变化和作用时间相关。这些酶类具有生物标记物的作用,对有机污染物的存在起到一定的指示作用,但这方面的研究还有待于进一步深入。这也是今后底栖动物有机污染研究的热点。

2.2 免疫系统

当今世界水产养殖业不断发现新病害并爆发大规模流行病[69],这可能与不断加剧的水体有机污染有关。有机污染物可以影响水生动物的免疫系统,导致致病性的增加[70]。因此,研究有机污染物对底栖动物免疫系统的影响,对于水产养殖的病害防治具有重要意义。

Wootton 等[71]的研究表明,暴露于不同浓度的菲,贻贝(*Mytilus edulis*)、海扇(*Cerastoderma edule*)和竹蛏(*Ensis siliqua*)的免疫调节系统均受到了不同程度的影响,但是贻贝(*Mytilus edulis*)的反映比较迟钝。其他研究还发现,PAHs类有机污染物对贻贝(*Mytilus edulis*)的溶酶体和细胞膜透性均有不同程度的损伤[72,73]。这些研究结果表明有机污染物对滩涂底栖动物的免疫功能有不利影响。目前关于这方面的研究还比较少,但是鉴于这方面的研究对于水产养殖的重要性,今后也有可能成为研究热点之一。

2.3 遗传毒性

污染物尤其是有机污染物的遗传毒性一直是人们关心的问题,以不同动物为材料的试验均表明 PAHs、PCBs 等有机污染物具有致突变作用[10,74~76],对底栖动物的研究也证明了这一点。

Large 等[6]将贻贝(*Mytilus edulis*)暴露在苯并[a]芘下之后,发现贻贝消化腺的 DNA 断线率增高,但是经过14d的高剂量暴露后 DNA 断线率又恢复到正常水平。试验者推测,暴露在高剂量的 PAHs 类污染物底下,贻贝体内产生了某种适应机制防止 DNA 的断线。Bolognesi 等[7]在受到 PAHs 和重金属污染的区域用贻贝(*Mytilus galloprovincialis*)进行生物监测。结果表明,单链 DNA 断线率和 PAHs 的含量微弱相关。野生贻贝比移植贻贝受到的污染严重,也因此表现出更多的染色体损伤(表现为微核率增高)。但是移植贻贝的 DNA 断线率比野生贻贝的高,试验者认为这是由于急性暴露造成的。实验还观察到染色体损伤的季节变化:染色体损伤在在9月份比5月份高,然而微核率却是5月份比9月份的高。与前面谈到的有机污染物含量的季节变化相比较,可以发现污染物含量的季节波动似乎与染色体损伤的季节变化一致,具体关系如何有待进一步深入的研究。

3 有机污染对底栖动物群落的影响

水体中的各类污染物能够以不同的方式进入到沉积物中,引起底质环境的变化,进而影响底栖生物的结构和组成。而底栖生物也可以通过摄食、排泄、掘穴等生命活动影响沉积物中污染物的分布。因此,底栖生物的结构和组成在一定程度上能够反映出滩涂环境的污染状况[77]。

大量的研究表明,有机污染物对底栖生物群落的组成和结构具有显著的影响[41,78~80]。很多研究表明,各种类型的有机污染物对底栖动物的生长活动范围(scope for growth,SfG)造成了显著的负面影响[81~83]。庄栋法等[84]通过研究柴油对底栖生物群落的影响,证明可以通过底栖生物群落结构和组成的变化来反映底质环境的质量状况。郭玉清等[85]曾利用渤海小型底栖动物数量的季节变动和自由生活海洋线虫与底栖桡足类数量之比的变动,对渤海潮下带沉积物的石油烃类污染状况进行了评价。这些研究表明,有机污染物对底栖动物群落的种类组成、种群数量和生长活动范围都有显著的影响。这也是有机污染监测的重要指标。

4 底栖动物有机污染生态学研究展望

底栖动物的有机污染生态学研究经过多年的发展,已经取得了一定的研究成果。目前的研究大多数集中在污染物的含量测定以及污染监测等方面,关于有机物对底栖动物影响的分子机制研究相对较少。而且,当前的研究对象局限于大型底栖动物,对小型底栖动物的有机污染生态学研究的报道很少。由于滩涂在渔业和水产养殖业中的重要作用,以及滩涂有机污染的复杂性和底栖动物多样性之间的变化关系等方面的研究尚未清楚,因此对如下几个方面的研究显得尤为重要:(1)继续开展有机污染物在滩涂底栖食物链中的积累、迁移、变化动力学研究;(2)加强有机污染物对滩涂底栖生物群落影响的研究,筛选指示生物;(3)开展有机污染物在底栖动物体内的分子生态毒理研究;(4)深入研究有机污染物对滩涂底栖动物生理生化,尤其是生物标记物的影响,了解底栖动物对有机污染的响应机制。

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