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Effects of seafloor macrolitter on marine organisms and its ecological impacts

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摘 要: 海底大型垃圾是海洋垃圾的重要组成部分,但目前关于海洋垃圾的研究主要集中于漂浮垃圾,而针对海底大型垃圾的研究较少。海底大型垃圾通常不易分解和迁移,这使其不仅能直接改变海洋环境和底质,还能通过影响海洋生物生存与生长进而威胁海洋生态系统健康。本文从定殖、缠绕、围困和摄食等 4 个角度系统地总结了目前海底大型垃圾对海洋生物的影响及其潜在生态效应的研究现状及进展,并对未来研究方向进行了展望。本文旨在从生物角度客观、全面地综述海底大型垃圾对底栖海洋生态系统的影响,以期为评估海底大型垃圾对海洋生物多样性的作用机制,及海底大型垃圾综合管控与治理提供科学依据。

关键词: 海底大型垃圾; 海洋生物; 生态效应

中图分类号: S 931.1 **文献标志码**: A

海洋垃圾是指海洋环境中具持久性的、人造的或经加工的固体废弃物[1-2]。海洋垃圾不仅严重影响全球或区域性海洋生态系统健康,还损害渔业、旅游业、娱乐和海上运输安全,是当前国际海洋环境领域的热点研究问题[3-5]。近年来,海洋垃圾已成为联合国、二十国集团(G20)、东盟(ASEAN)和亚太经合组织(APEC)等国际合作框架以及双边或多边高级别会谈中环境领域的重要议题。如在中韩政府间高级别会谈中,海洋垃圾连续五年都是主要议题。海洋垃圾广泛分布于海洋的各个角落,包括海滩、海表、海底及各海洋生物类群的内部和表层等[6-7];甚至在深达 10 898 m 的马里亚纳海沟中也有发现[8-9]。海洋垃圾不仅能直接改变海洋环境,还能通过影响海洋生物的生命活动进而间接调控海洋生物群落结构、生物多样性和食物网能流格局,影响海洋生态系统健康。研究[10]表明,海洋垃圾中有 15% 为海表面的漂浮垃圾,另有 15% 赋存于不同水层中,剩余的 70% 则沉降至海底。受观测手段、研究方法等限制,目前关于海洋垃圾的研究主要集中于漂浮垃圾,而针对海底垃圾,特别是海底大型垃圾的调查、研究[6,11-12]较少。海底大型垃圾是指沉降至海底的直径大于 25 mm 的海洋垃圾,主要为塑料类、玻璃类、饮料罐、抛弃渔网、织物类及金属类等。在海洋环流及其他环境因子作用下,海底大型垃圾可经长距离迁移而在海底特定区域聚集,直接或间接地影响该区域海洋生物的生存与生长。

海底特殊环境(黑暗、低温、高压和低能量流动等)使得聚集而来的大型垃圾不易分解和迁移,从而直接改变海底环境和底质并进一步影响海底生态系统的稳定性[13-14]。特别是海草床、海绵场和珊瑚礁等敏感海域,海底垃圾更易对其生态系统造成不可逆的严重损害。以珊瑚礁为例,评估模型显示目前亚太地区的珊瑚礁生态系统中分布着大约 111 亿个塑料垃圾碎片,而到 2025 年这一数字则可能再增加 40%[15];海底大型垃圾对珊瑚礁的破坏与损伤严重威胁 418 种珊瑚礁生物的种群繁衍与扩散[16]。同时,海底大型垃圾通常是材质坚硬的固体材料,导致一些固着性生物集中或附着于其表面进行扩散,并通过生物级联效应改变底栖生态系统。这一现象在近海、

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大洋、深远海与极地等不同海区中均有发现[17-19]。近年来又有学者发现,海底大型垃圾的聚集区(特别是深海底),可能是底栖生物多样性的热点区域。如在西沙海槽大型垃圾聚集地采集的 33 块塑料垃圾碎片上,SONG 等[20]发现其表面的生物群落具有高物种多样性,包括深海特有的钵水母纲水螅体、水螅虫纲水螅体、冷水珊瑚、无板纲贝类甚至特化的寄生扁形动物等 49 个物种。总之,海底大型垃圾分布范围广、降解性极低,能通过定殖、缠绕、围困和摄食等多种方式影响海洋生物的生命过程,威胁海洋生物多样性和生态系统健康。据统计,海底大型垃圾对超过 3 400 种海洋生物的生命活动存在不同程度的影响。不同海洋生物类群对海底大型垃圾的生态响应程度不仅取决于大型垃圾的理化性质和分布范围,更与不同物种的生态习性及生活史特性密切相关[19,21]。如生活于巴西海岸的 2 种海豚,弗西豚(*Pontoporia blainvelli*)和圭亚那白海豚(*Sotalia guianensis*),因摄食习性差异而对大型垃圾表现出不同的摄食敏感度[22]。在漫长的地质演化过程中,海洋生物逐渐进化出独特的生理机制以应对特定海洋环境下各环境因子(温度、盐度、pH、碳酸盐质量浓度等)的波动性变化。但是,海底大型垃圾是由于人类活动而新出现的外源性环境因子,这导致各海洋生物类群均未进化出对海洋垃圾的适应机制,海洋生物更易受海底大型垃圾影响而出现不同的生态效应。本文将从定殖、缠绕、围困和摄食等 4 个方面总结海底大型垃圾对海洋生物生长、生存的影响及其所产生的生态效应,以期为评估海底大型垃圾对海洋生物多样性的潜在影响提供科学依据,也为海底垃圾综合管控与治理提供理论基础。

1 定殖作用

海底大型垃圾对海洋生物的定殖作用主要表现在 2 个方面:(1)为海洋生物(包括本地物种和外来物种)的扩散提供固着“载体”;(2)为多种海洋生物的共生性定殖提供“人工栖息地”。海底大型垃圾能通过增加聚集区海底环境的空间异质性来为一些本地物种提供扩散基础[8,23-24]。以北黄海营固着生活的须毛高龄细指海葵(*Metridium sensile fimbriatum*)为例,海底大型垃圾的聚集为该物种提供了更多的扩散位点,是其在本海域爆发性生长的重要环境驱动力[25];数次北黄海底拖网调查发现,渔网、玻璃瓶、橡胶手套、织物和塑料等大型海底垃圾为须毛高龄细指海葵的扩散生长提供了固着“载体”(图 1),然后通过食物级联效应改变该海域生态系统食物网能流格局,进而调控底栖生物群落结构、改变底栖生态系统结构和功能。

海底垃圾的聚集过程还能为附着在垃圾上的外来物种提供入侵“载体”,使其在新的栖息地定居、繁衍,在与本地物种的生态位竞争中占据优势并成为新的优势种,对本地生态系统造成颠覆性改变。RECH 等[26]和 DE-LA-TORRE 等[27]在近岸海洋渔具垃圾中发现了 8 种与渔业活动密切相关的入侵种,这些物种在新的海底环境中的定殖、扩散过程对海底大型垃圾有着高度依赖性。此外,海洋生物在海底的定殖过程可能与大型垃圾的类型密切相关。研究[28-30]表明,一些苔藓动物和海鞘动物在入侵、定殖过程中更偏好塑料垃圾而非其他垃圾;而藤壶在定殖过程中更偏好玻璃类垃圾而非塑料[31]。然而,目前关于海洋生物定殖过程中对不同类型海底大型垃圾的选择性研究尚处于起步阶段,相关作用机制亟待进一步探索。

海底大型垃圾聚集区通常具有稳定的水文生态环境,为多种底栖生物的共生性定殖提供环境基础,使其成为潜在的生物多样性热点区域。在地中海水域,科学家多次观察到海底废弃的渔网和延绳上出现了多种终生营固着生活或生活史中部分阶段营固着生活的底栖物种,包括多毛类、水螅类、海绵、被囊类、苔藓虫、珊瑚等多个海洋生物类群,形成了一个相对稳定的生物群落结构[32-34]。此外,相关研究表明,在海底大型塑料中大量附着的水螅体可能是周边海域的水母释放源头。水螅体能在海底大型垃圾上附着定殖并存活数十年,一旦水环境条件适宜,能迅速分裂成大量碟状体,进而驱动水母爆发、诱导海洋生物群落衰退性演化[35]。

2 缠绕作用

海洋垃圾对海洋生物的缠绕作用是威胁其多样性的重要原因之一。《生物多样性公约》秘书处报告称,所有海龟种类、45% 的海洋哺乳动物种类和 21% 的海鸟种类都可能受到海洋垃圾

缠绕而出现损伤、死亡[36-37]。截至 2015 年，共有 693 种海洋生物因海洋垃圾的缠绕和误食而出现种群层面的大幅下降，其中约有 17% 为 IUCN 红色名录物种[38]。缠绕在海洋生物体表的大型垃圾不但会干扰海洋生物的迁移、摄食、呼吸和繁殖等生命活动过程[39]；还可能造成海洋生物体表受伤，增加其被病毒感染或被捕食者猎杀的风险[15]。

a. 2017 年 1 月；b. 2019 年 5 月；c. 2018 年 8 月；d. 2019 年 11 月。
a. Jan, 2017; b. May, 2019; c. Aug, 2018; d. Nov, 2019.

图 1　“北斗”号北黄海底拖网调查中的须毛高龄细指海葵

Fig. 1　*Metridium sensile fimbriatum* in the bottom trawl survey in the northern Yellow Sea by R/V “Beidou”

在海底生活环境中，营固着生活的无脊椎动物，如脆弱而长寿的珊瑚和海绵，以及在海底生活的其他物种最可能因海底大型垃圾的缠绕作用而增加其生态风险[40]。珊瑚礁、海绵场和海草床等敏感性底栖生态系统易受海底大型垃圾缠绕而出现生态危机[16,41]。珊瑚礁生态系统是生物多样性程度最高的生态系统之一，同时也极为敏感、脆弱，易因外界环境变化而出现大面积系统性崩溃。海底大型垃圾的缠绕作用既会使部分珊瑚面临窒息风险，也可能通过摩擦引发珊瑚组织物理损伤，使其更易因寄生虫、细菌和污染物的影响而走向病变衰退[15,17,42-43]。海底大型垃圾所带来的严重损伤往往超过珊瑚自身愈合、恢复的能力，导致珊瑚群体大批量死亡[44-45]。此外，海底大型垃圾还会直接缠绕在珊瑚礁生物体表，使其面临窒息缺氧和机体损伤等胁迫，最终走向死亡。据报道，佛罗里达礁岛的珊瑚礁生态系统中的海绵动物和刺胞动物 84% 的个体因聚集于此的废弃渔具影响而部分或全部死亡[46]。海绵场是另一个对海底大型垃圾的缠绕作用极为敏感的生态系统。PARGA 等[19]通过分析从北冰洋海绵场采集到的多个海绵标本发现，近三分之一的海绵个体中存在缠绕着的塑料垃圾碎片，这可能与海绵场生物群落的受损甚至衰落密切相关。

3　围困作用

造成海洋生物围困的海洋垃圾主要是在海洋捕捞过程中废弃、丢失和丢弃的渔具，简称“废弃渔具”（Abandoned, lost or otherwise discarded fishing gear，ALDFG），包括陷阱渔具、渔线和渔网等，并且由于其成分不可降解可在海洋里留存很长时间。ALDFG 在海底的密度和数量不仅与水文和地貌密切相关，更取决于附近水域的渔业强度。如在圣维森特岛 São Vicente 海底峡谷海底垃圾中废弃渔具占垃圾总量的 89%[4]，第勒尼安海海底垃圾 89% 是渔具（主要是渔线）[17]。ALDFG 不仅会污染海洋环境，还会引发幽灵捕捞[40]。体型较大、繁殖缓慢、繁殖力低、生长缓慢、寿命较长和对环境变化较敏感的大型海洋动物更易受到幽灵捕捞的伤害。世界动物保护协会表示，每年约有 13.6 万只海豹、海狮、鲸类、海龟和海豚等大型海洋动物因幽灵捕捞而死亡。此外，幽灵捕捞还会影响渔业，一方面幽灵捕捞在某些渔场渔获量可以占到 5% ~30%[47]；另一方面幽灵捕捞还会造成某些渔业产量的急剧下降，如加拿大圣劳伦斯湾雪蟹（*Chionoecetes opilio*），渔民在 23 年间丢弃的约 19 000 个陷阱渔具可能导致 94.6% 的雪蟹被幽灵捕捞，造成高达 48.2 t 的产量损失[41-42]，大约 2 000 t 蓝蟹在美国路易斯安那州因幽灵捕捞而损失，约占其渔获量的 10%[48]，并且在废弃捕蟹笼中，美国红鱼（*Sciaenops ocellatus*）也被发现；在马斯喀特水域陷阱渔具实验证明，每个抛弃陷阱渔具每天可以造成 1.34 kg 海洋生物死亡，陷阱渔具抛弃 3 个月和 6 个月后，每个抛弃陷阱渔具可累计造成 67.27 kg 和 78.36 kg 海洋生物死亡[49]。另外，一些海洋甲壳类进入这些陷阱渔具后可能造成个体间捕食、自残、饥饿概率上升，进而导致附肢残缺和健康状态的普遍下降，还会吸引其他海洋生物进入到陷阱渔具[50]。

4 摄食作用

海洋生物对海底大型垃圾的摄食不仅会影响自身的生存与生长，还可能通过生物级联效应改变生物群落结构和食物网能流格局，影响海洋生态系统健康。越来越多的海洋生物已被证明会摄食各种类型的海洋垃圾[51-52]；这种摄食过程既包括将垃圾误认为猎物的主动摄食[52-54]，也可能是其在捕食猎物时的误食或二次摄食（猎物体内有海洋垃圾）[55-57]。研究表明，部分海洋垃圾（特别是塑料垃圾）能在海洋中释放某种信息性化学物质，从而吸引大型海洋生物对其进行摄食；这些大型海洋生物主要是海龟、鲨鱼、鲸鱼、海豚、海豹和海鸟等[58-60]。其中，海龟和齿鲸的生理机能使它们难以消解摄入体内的垃圾，因此经常在它们胃中发现大量塑料垃圾[61-62]。据统计，目前至少有 46 种鲸类（约占总种数 56%）胃中检测到了垃圾的存在，部分种类的垃圾摄食率甚至高达 31%[63]。大型垃圾可能直接导致海洋动物胃肠道堵塞或受损，影响其摄食、生长、生存等生命过程，产生致死或亚致死效应[34,64-65]。此外，海洋生物不同的生态习性也决定着其对海洋垃圾的摄食敏感性。以巴西海岸的两种海豚为例，营底部摄食的弗西豚比营海表摄食的圭亚那白海豚胃中垃圾占比更高[22]。海底大型垃圾表面会吸附某些有毒化学物质，如杀虫剂，持久性有机污染物、重金属、放射性物质和除草剂等[66-68]。海洋动物摄入垃圾后，这些有毒化学物质进入其身体并逐渐蓄积，然后经食物链传递使毒素在高营养级生物体内富集，以生物放大作用将毒性扩散到整个海洋生态系统，最终危害人类的健康[69]。研究已经证实，蛤蜊（*Scrobicularia plana*）、端足类（*Talitrus saltator*）和珊瑚（*Stylophora pistillata*）等能把通过摄食塑料而进入体内的化学污染物转移到底栖生物群落中[70-72]，导致污染物的毒素经生物蓄积和生物放大扩散到食物网的各个营养级，造成严重的生态影响[73-74]。

5 展望

防止海洋污染，保护生态环境是联合国 2030 年可持续发展议程制定的重要目标。海洋垃圾污染是海洋污染的重要组成部分，但其调查、评估、治理等仍是一个国际性的难题。我国对海底大型垃圾的监测工作起步较晚，主要集中在海滩、沿岸、河口、海湾、沿海休闲水域、海洋保护区、海水养殖区和港口等功能性水域[75-81]，深水区海底大型垃圾的观测仅见于黄海和东海北部水域[82]，海底大型垃圾调查手段主要为拖网调查、潜水观测和基于 ROV 的视频图像记录。基于海底大型垃圾调查的高成本和高难度，这类监测活动不可能覆盖所有海区。因此，未来需要研发普适性海底大型垃圾量化监测技术，实现海底大型垃圾种类、密度、来源等的常规监测，海底大型垃圾敏感区域、热点区域长期定量监测，探索

海底大型垃圾的搬运和扩散机制,为海洋垃圾的综合治理和有效管控提供数据支撑。

海底大型垃圾主要通过定殖、缠绕、围困和摄食等4种方式影响海洋生物,进而产生一系列生态效应,如何精准评估海底大型垃圾带来的生物级联效应是实现海洋生物资源保护的关键。现在仍有许多基础性科学研究问题亟待解决,如:海底大型垃圾对某种生物的影响是如何通过生物级联效应扩大至生态效应? 对底栖生物群落结构、生态系统的作用机制是什么? 解决这些问题对客观认识海底大型垃圾对海洋生态系统的影响,制定合理的垃圾治理对策具有重要意义。此外,在全球气候变化和人类活动日益加剧的背景下,海底大型垃圾还可能与海洋酸化、富营养化等外源性环境因子变化相互作用,协同影响海洋生物的生命过程。因此,在评估海底大型垃圾对海洋生物的影响时还应同时监测其他环境因子变动,从而更为全面地量化、评估海底大型垃圾的生态效应。

另外,我国尚未出台健全的垃圾监测与评价体系以适应日益深化的海洋环境监测需求[83]。高磊等[84]提出了基于压力-状态-响应(Pressure-state-response,PSR)指标框架的海洋垃圾综合评价体系,利用层次分析法确定评价海域的海洋垃圾等级。海底大型垃圾与海洋生物的广泛联系表明,在制定评价体系的过程中,不仅要考虑垃圾种类、密度、来源等量化指标,还应同时分析评价该区域生物资源现状及潜在变化趋势,从而为后续综合管控与治理提供更为全面的科学依据。

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Effects of seafloor macrolitter on marine organisms and its ecological impacts

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Abstract: Seafloor macrolitter has been recognized as a major part of marine litter, while it is the least investigated fraction of marine litter. Seafloor macrolitter is not biodegradable and transferable. Therefore, it can directly alter the marine environment and bottom sediment, and indirectly threat the health of marine ecosystem by impacting the survival and growth of marine organisms. This study retrospected the studies on the ecological impacts of seafloor macrolitter from the perspective of colonization, entanglement, encirclement and ingestion, and pointed to future developments that are required to address the estimation of seafloor macrolitter. Knowledge of this study could provide scientific support for the evaluation of potential impacts on marine biodiversity, as well as the monitor and management of seafloor macrolitter.

Key words: seafloor macrolitter; marine organisms; ecological impacts