第 47 卷　第 2 期　　渔 业 科 学 进 展　　Vol.47, No.2
2026 年　4 月　　PROGRESS IN FISHERY SCIENCES　　Apr., 2026

DOI: 10.19663/j.issn2095-9869.20250421002　　http://www.yykxjz.cn/

李贤, 孙雯, 苏俊洁, 段姗杉, 张翔宇, 吴乐乐. 基于文献计量分析鱼类对人为噪声的响应. 渔业科学进展, 2026, 47(2): 168–179
LI X, SUN W, SU J J, DUAN S S, ZHANG X Y, WU L L. Bibliometric analysis of fish responses to anthropogenic noise. Progress in Fishery Sciences, 2026, 47(2): 168–179

基于文献计量分析鱼类对人为噪声的响应*

李贤① 孙雯 苏俊洁 段姗杉 张翔宇 吴乐乐

(中国海洋大学水产学院　山东　青岛　266003)

摘要　人为噪声通常指由人类活动产生并释放到环境中的各种噪声，它在水下环境中对鱼类及其他水生生物可能产生显著的负面影响。随着全球船舶运输、海上工程建设、水上娱乐活动以及集约化水产养殖等活动的快速发展，人为噪声对鱼类福利的影响已引起环保组织、政府部门、科研机构、水产养殖行业从业者和消费者的广泛关注。近些年来，人为噪声对鱼类福利的研究数量逐渐增多，但大多数研究集中于单一鱼类对噪声响应分析，缺乏从鱼类栖息环境分类的视角系统探讨不同生态类型鱼类对噪声响应的差异性。本文通过文献计量分析方法，概述了鱼类对人为噪声响应的研究进展，并分别探讨了自然环境和养殖环境下的人为噪音对鱼类生长、生理、行为等福利参数影响的研究现状。本文对提升公众认知、助力制定指导政策、推动相关领域交叉学科发展以及技术创新具有重要意义，通过梳理人为噪声和鱼类响应之间的复杂关系，旨在促进人类活动与鱼类赖以生存的水下声景环境的协调，提升鱼类福利，实现经济与生态效益的双赢。

关键词　鱼类；人为噪声；文献计量；鱼类福利

中图分类号　S91　**文献标识码**　A　**文章编号**　2095-9869(2026)02-0168-12

声音在海洋中具有远距离传递信息的优势。工业革命前，海洋声景由地质活动产生的自然声与生物发声构成，这些声音是海洋生物生存与繁衍的关键信息来源(Duarte *et al*, 2021)。工业革命后，由于人类活动的影响，人为噪音大量增加，根据其频率和强度特征，可分为两大类：低频平稳噪音和高强度脉冲噪音。低频平稳噪音主要由各种船舶产生(Dyndo *et al*, 2015)，而打桩(Kastelein *et al*, 2015)、水下爆破(张冬洋等, 2023)、地震勘探(Guan *et al*, 2016)和主动声纳(Halvorsen *et al*, 2013)等属于高强度脉冲噪音，已被证实可对鱼类造成诸多负面影响。

人类对海洋中人为噪声的关注最早可以追溯至1971 年，Payne 等(1971)研究发现，人为噪声干扰了须鲸的正常繁殖交流。随后美国政府于 1972 年颁布《海洋哺乳动物保护法》，并设立美国海洋哺乳动物委员会(U.S. Marine Mammal Commission, USMMC)(Roman *et al*, 2013)。在此之后，针对人为噪声的影响问题，美国海洋能源管理局(Bureau of Ocean Energy Management, BOEM)开创性地进行了鲸类动物暴露于工业活动噪音的行为反应的研究(Guan *et al*, 2023)。随着海洋哺乳动物对人为噪声响应的研究不断推进，逐渐把关注点向其他的海洋动物转移。1990 年已有相关研究表明，人为噪声会对鱼类的交流产生掩蔽效应，并导致鱼类听觉受损和行为改变。同样，水产养殖环境下鱼类的生长繁殖也会受到人为噪声的影响，并可能导致鱼类养殖产量与质量的下降(Myrberg, 1990; De Jong *et al*, 2020; Nedelec *et al*, 2015)。

---

* 国家重点研发项目-深远海养殖大规格苗种行为特征及与环境互作机制(2024YFD2400101)资助。

① 通信作者：李　贤，教授，Email: lixian@ouc.edu.cn

收稿日期: 2025-04-21, 收修改稿日期: 2025-05-07

离岸与陆基养殖环境中，不同来源和类型的人为噪声能够被大多数养殖鱼类所感知。其中离岸养殖的人为噪声可按照离岸远近的不同进行区分，如近岸鱼类养殖场人为噪声包含了沿海开发水下爆破噪声、捕捞作业噪声、船舶通行噪声、疏浚噪声等(Wong *et al*, 2022)；深远海大型养殖网箱与养殖平台除这些外部环境噪声，自身的投喂、动力等系统产生的噪音也会对养殖鱼类的健康造成一定影响(Puig-Pons *et al*, 2021)。在陆基养殖系统中，不同的生产管理模式导致人为噪声来源差异较大，池塘养殖噪声来源较为单一，主要来自养殖人员活动以及增氧设备的运转；而在工厂化养殖系统中，增氧机、投饵机、过滤系统和水泵等设备不仅产生大量噪音，且噪音相互交织，增加了噪音的复杂性(Zhang *et al*, 2023a、b; Popper *et al*, 1976; Davidson *et al*, 2009; Jiang *et al*, 2024b)。

世界动物卫生组织(World Organization for Animal Health, OIE)将动物福利(animal welfare)定义为动物的一种生存状态，良好的动物福利状态包括健康、舒适、安全的生存环境，充足的营养，免受痛苦、恐惧和压力，表达动物的天性，良好兽医诊治，疾病预防和人道的屠宰方式(Brambell, 1965)。在动物福利研究的整体框架下，鱼类福利作为水生动物福利的重要分支，受人类活动影响最为直接且与水产养殖产业及海洋生态保护密切相关。随着鱼类福利理念在公众认知、养殖业中的日益普及，鱼类对人为噪声响应的研究不仅对提升养殖鱼类福利水平具有重要意义，同时也在渔业经济效益优化、海上作业活动规范以及水域生态环境保护等方面展现出广泛的应用价值。一方面，研究自然水生环境下人为噪声对鱼类的影响，有利于为政府部门制定环境保护与资源管理政策提供数据支持；另一方面，水产养殖从业者在了解人为噪声对鱼类的影响后，能够为养殖鱼类创造更适宜的水下声景环境，提升水产品质量和经济效益。

1　鱼类对人为噪声响应的研究进展

鱼类受人为噪声影响的文献最早发表于 1990 年，研究机构为迈阿密大学罗森斯蒂尔海洋科学学院(Myrberg, 1990)。在此之前，许多学者已经证实了噪音对鱼类的生长与听觉有负面影响，如 Banner 等(1973)提及噪音会干扰两种河口鱼类的早期发育，又如 Popper 等(1976)研究表明，金鱼(*Carassius auratus*)听力系统在强烈声刺激下受损等。

为全面了解全球范围内鱼类对人为噪声响应的研究进展，本文使用 VOSviewer 软件对所有有关人为噪声对鱼类影响的文献进行可视化分析，文献数据源自 Web of Science (WOS)，通过可视化分析可有效揭示全球科研网络中不同研究团队、机构和国家之间的合作模式(Li *et al*, 2018)。本文采用 WOS 平台上的 Science Citation Index Expanded (SCI-E)数据库为数据源，文献检索时间范围设定为 1990—2024 年，在此期间以主题词“Fish”和“Anthropogenic noise”(或“Man-made noise”)，辅以关键词“Underwater noise”，文章类型为“article”或“review”进行检索。VOSviewer 分析主要通过提取并筛选文献中的关键词、研究国家与研究机构，并通过多维网络图谱呈现分析结果的可视化。图谱中节点的尺寸映射文献信息出现的频次强度，节点间连线的粗细表征关联强度。在叠加分析中，节点颜色由浅至深代表对应信息出现的时间范围。文献可视化分析从多个维度助力科研人员深入理解鱼类对人为噪声响应的研究现状，为进一步研究提供科学指引。

1.1　关键词分析

鱼类对人为噪声响应研究相关数据时间跨度为 1990—2024 年，总计发文量 283 篇，并主要集中在近 5 年(图 1)，表明人为噪声对鱼类的影响已逐渐成

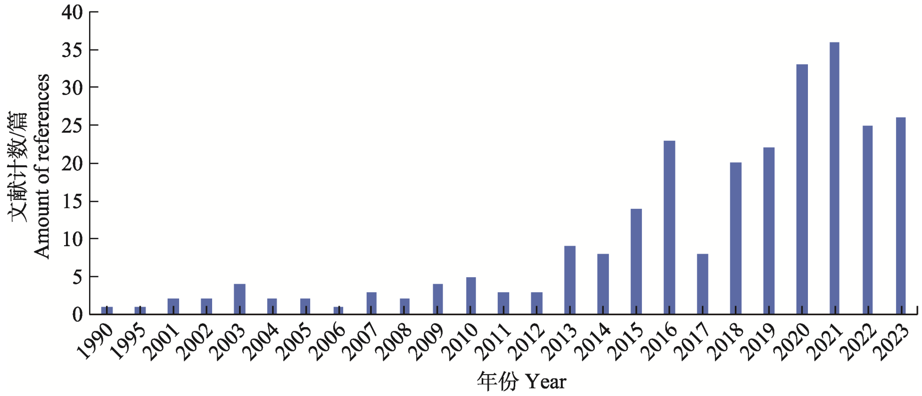

图 1　鱼类对人为噪声响应的全球文献计量统计

Fig.1　Global bibliometric statistics of fish responses to anthropogenic noise

为关注热点。经 VOSviewer 软件对所有包含人为噪声及鱼类主题的文献进行关键词提取，将重复出现与无意义关键词筛去后得到结果如图 2 所示。结果显示，在探究鱼类对人为噪声响应的过程中，行为(behavior)、听觉(hearing)、压力(stress)、船舶噪声(ship noise 与 boat noise)、声通讯(acoustic communication)、虹鳟(*Oncorhynchus mykiss*)、生长(growth)和粒子运动(particle motion)等是讨论次数较多的关键词。

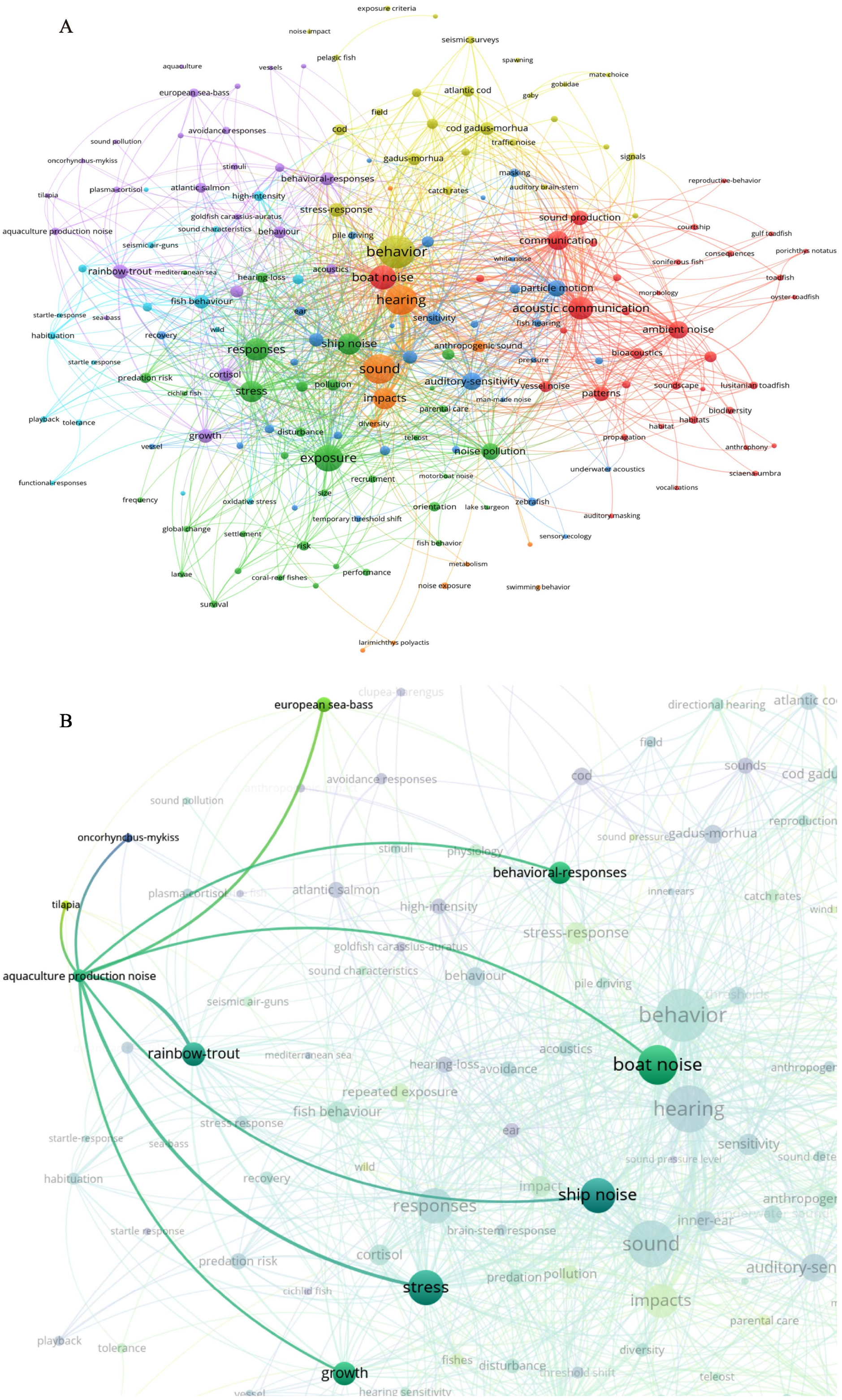

图 2　关键词分析(A 为整体分析，B 为聚焦于水产养殖来源噪声分析的截选)

Fig.2　Keywords analysis (A represents overall analysis, and B represents excerpt focusing on noise analysis from aquaculture sources)

结果表明，鱼类的行为、听觉与压力响应是科研人员在人为噪声影响研究中最为关注的问题。其中，研究者最早发现鱼类受人为噪声影响后，繁殖、运动与摄食以及幼鱼定向等多种行为模式会发生改变(De Jong *et al*, 2018)。船舶噪声与打桩声对鱼类运动与摄食方面的影响同样不可忽视，例如船舶的存在与移动导致北极鳕(*Boreogadus saida*)的觅食搜索行为减少，快速移动与长距离的旅行行为增加，并且破坏北极鳕的进食环境(Ivanova *et al*, 2020)。近距离打桩声引发大西洋鳕(*Gadus morhua*)应激反应(stress-response)，远离打桩位置(van der Knaap *et al*, 2022b)。与此同时，鱼类听觉受人为噪声影响的相关研究也不断取得新进展，Wong 等(2022)研究发现，斑马鱼(*Danio rerio*)暴露于白噪声(150±10 dB re 1 μPa)后，听觉阈值变化明显，并引发焦虑行为。随后 Badlowski 等(2024)指出，大西洋鲱(*Macrodon ancylodon*)听觉系统在短期噪声暴露下具有一定耐受性，但长期重复暴露会使听觉敏感度下降，不利于躲避捕食者。因此，听觉掩蔽(auditory masking)、听力损失(hearing-loss)和生长(growth)等关键词与鱼类对人为噪声的响应密切相关。虹鳟作为一种人为噪声影响研究最多的全球性养殖品种，早在 2007 年，Wysocki 等(2007)评估了水产养殖生产噪声(115~150 dB re 1 μPa RMS)对虹鳟听力敏感性的影响，结果表明不同批次的虹鳟听力阈值存在差异。后续该团队发现，高强度噪声(149 dB re 1 μPa RMS)初期抑制虹鳟生长，但后期虹鳟会适应噪音，表现补偿生长并体现出更高的存活率(Davidson *et al*, 2009)。近年来，噪音对欧洲鳗鲡(*Anguilla anguilla*)、鲣鱼(*Katsuwonus pelamis*)、大黄鱼(*Larimichthys crocea*)和小黄鱼(*Larimichthys polyactis*)等的研究逐渐增多，并随着检测技术不断发展，填补了鱼类对噪声分子层面响应机制的空白。Jiang 等(2024a)采用代谢组学与转录组学联合分析，揭示了长期噪声胁迫对小黄鱼下丘脑–垂体–肾上腺轴(Hypothalamic-Pituitary-Adrenal Axis, HPA 轴)调节影响，噪音会导致小黄鱼体内代谢紊乱、引发氧化应激损伤与相关疾病，为探查人为噪声对鱼类福利影响提供了新的视角。

叠加分析结果(图 2B)显示，科研人员近些年对养殖噪声的研究逐渐增多。Filiciotto 等(2013)通过实验对比皮质醇、血糖等血液指标，表明随机的近海养殖噪声与海洋声景序列相比于低水平环境噪声有利于金头鲷(*Sparus aurata*)幼鱼减轻压力，对其生长性能有积极影响；Radford 等(2019)对比商业网箱、土塘和循环水养殖系统(Recirculating Aquaculture System, 以下简称 RAS)的声音背景，分析了这些噪音对于常见养殖鱼类的影响，并提出 RAS 中存在的噪音比土塘环境噪声水平更高，且多数养殖系统噪声集中在低频段(100~500 Hz)，这恰好处于大部分养殖鱼类的听觉范围内。随着 RAS 养殖模式的发展，聚焦于 RAS 噪声的研究也在不断增加(Duan *et al*, 2025)。Hang 等(2021)研究了 RAS 噪音对大口黑鲈(*Micropterus salmoides*)的生长、生理与行为等福利参数影响，发现 RAS 噪声抑制了大口黑鲈幼鱼的生长，损害了生理机能，并干扰了鱼群的游泳行为；他们进一步评估了 RAS 不同频率噪声对大口黑鲈幼鱼的影响，指出低频噪声会降低集体摄食信号的传播效率并使摄食强度下降(Hang *et al*, 2024)。

1.2　研究国家分析

网格分析可见(图 3A)，美国、英国和加拿大是开展人为噪声对鱼类影响研究较多的国家，这与其水产养殖业规模、环境保护意识及公众认知密切相关。以美国为例，其水产养殖历史可追溯至 19 世纪，1871 年成立的联邦鱼类和渔业委员会旨在加强鱼类增殖(薛晓明等, 2013)，随着养殖机构的崛起和养殖规模的不断扩大，养殖技术也在不断突破和创新(Nash, 2011)。美国在发展鱼类养殖的同时，逐渐开始关注水产养殖环境中的潜在干扰因素，从最初单一探究高强度人为噪声对鱼耳的损伤，逐渐拓展到综合分析鱼类在听觉、生理和生长等多方面对各类人为噪声的响应过程(Bart *et al*, 2001; McCauley *et al*, 2003; Popper *et al*, 2009)。随着科技的进步，研究尺度已延伸至从水下声景粒子加速度的测量(Jones *et al*, 2022)到鱼类振动信号的接收这一过程(Roberts *et al*, 2023)，人为噪声对鱼类福利研究的深度与广度不断增加。

叠加分析(1990—2024 年)显示，近 5 年来，意大利和中国越来越多的学者参与了鱼类对人为噪声响应的研究。2007 年至今，意大利共发表了 24 篇相关文献，其中近 5 年有 12 篇。意大利学者从不同角度探究了海洋人为噪声与鱼类行为、繁殖等方面的关系。Ceraulo 等(2021)采用被动声学方法研究船只噪声对鱼类发声的影响；Siddagangaiah 等(2022)调查了台湾叫姑鱼(*Johnius taiwanensis*)等石首鱼科鱼类群体发声类型对风电场建设与运营期间噪声的反应；该团队还在 2024 年通过长期监测声学环境，评估人为噪声对鱼类发声行为的影响(Siddagangaiah *et al*, 2024)。此外，近年来还有部分学者以斑马鱼这一模式生物为研究对象，探究人为噪声影响其听觉系统，导致生理和行为应激的机制(Banner *et al*, 1973; Lara *et al*, 2021、2022)。通过国家间关系分析看出，1990—2024 年期

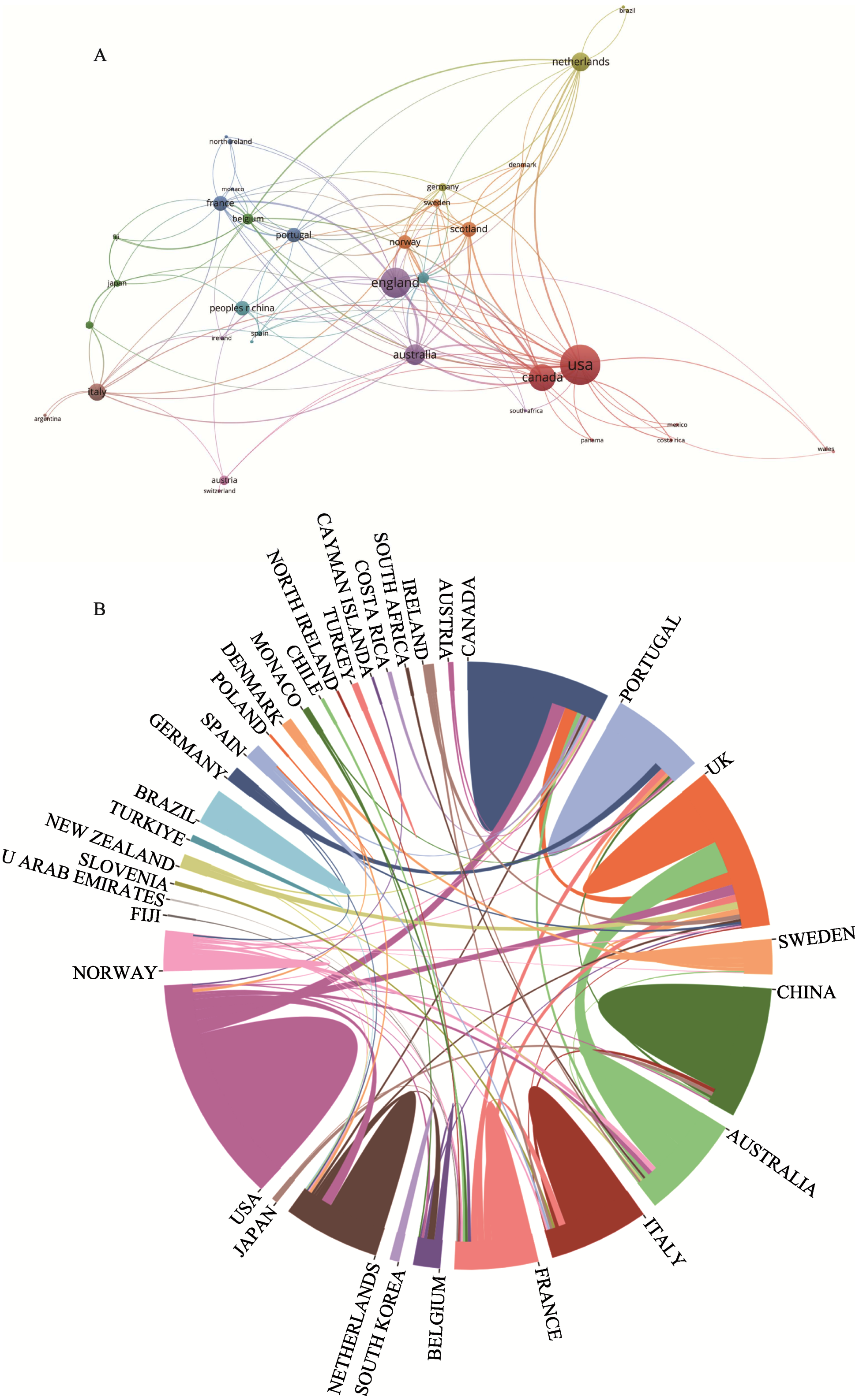

图 3 国家分析(A 为网络图，B 为可视化弦图)

Fig.3 National analysis (A represents network diagram, and B represents visual chord diagram)

间美国发文量最多，且与多国联系紧密；意大利与英国、法国和挪威合作紧密，而中国则与葡萄牙和新西兰的合作较为紧密。

尽管中国在鱼类响应人为噪声的研究起步较晚，但相关研究已涵盖了多种典型人为噪声源。贾晓平等(2002)发现大型爆破作业后 24 h，受影响区域内的鱼

卵和仔鱼数量显著减少且无明显恢复迹象。国内学者基于频率特性对海洋噪声进行了系统性分类(张国胜等, 2012)。殷雷明等(2017)研究发现，网箱养殖的大黄鱼受起网捕鱼作业噪音的干扰显著高于船舶噪声影响。随着研究拓展，在前期风电场噪声特性分析基础上，国内作者发表了海上风电场水下噪声对鱼类听觉敏感性及声学通讯的干扰研究(张博等, 2016; 牛富强等, 2021; Zhang *et al*, 2021)。王瑄等(2025)指出，水利工程产生的水下泄洪声会显著增加草鱼幼鱼的应激反应并造成鱼生理损伤。

1.3　研究机构分析

网格分析和叠加分析(图 4A)可见，埃克塞特大学(University of Exeter)发文量在所有机构中排名第一，其次是布里斯托大学(University of Bristol)，这两所位于英国的院校在海洋生物科学、海洋生态与气候变化以及水产相关领域有广泛研究。这两所院校已发表 35 篇人为噪声对鱼类福利影响的研究论文。此外，发文量较多的机构还包括莱顿大学(Leiden University)、马里兰大学系统(University System of Maryland)、温莎大学(University of Windsor)等。

图 4B 显示，中国研究机构发文量并非排在最前列，这与国人开展人为噪声对鱼类影响研究起步较晚和机构较分散有关，我国发文量最多的单位是台湾海洋大学(Taiwan Ocean Univ)，其次为中国科学院(Chinese Acad Sci)、浙江大学(Zhejiang Univ)、上海海洋大学(Shanghai Ocean Univ)以及中国海洋大学(Ocean Univ China)等。

由此可见，鱼类响应人为噪声的研究尚处于新兴阶段，且各研究单位间仍以离散化独立研究居多，文章发表主要集中在近 5 年，这一显著的时序分布特征直观反映了人为噪声对鱼类福利影响正在快速崛起，成为水生生态和水产养殖学研究的新兴热点。学术关注度的跃升呼应了当前社会对“绿色发展”理念的迫切需求，即在持续推进海洋经济发展的同时，必须更加科学地平衡人类活动与生态保护、养殖效率与养殖动物福利之间的复杂关系。

2　自然环境下鱼类对人为噪声的响应

自然环境下的人为噪声主要包括船舶噪声、海上风电场噪声、地震勘测噪声以及施工噪声等。鱼类人为噪声的响应可分为以下几个方面：

(1) 游泳行为层面：蓝鳍金枪鱼(*Thunnus thynnus*)在船舶靠近时会改变游泳方向并增加垂直运动，导致鱼群结构松散且游泳行为失去协调，小型船舷外发动机噪声还会使其呈现不安状态，表现出快速转向与速度变化(Sarà *et al*, 2007)。太平洋鲱(*Clupea pallasii*) (van der Knaap *et al*, 2022a)、金头鲷(*Pagrus auratus*)等鱼类面对船舶噪音时也表现出类似的躲避行为(Mensinger *et al*, 2018)。此外，大西洋鳕对打桩噪声与风电场低频噪声均会产生行为响应，但由于频率、强度和持续时间的不同，行为改变存在差异(van der Knaap *et al*, 2022b; Cresci *et al*, 2023)。近年研究表明，鱼类对人为噪声的行为响应还体现在反捕食与觅食方面，欧洲鳗鲡在船只通过港口时反应力下降，更易被捕捉，且侧化行为减少，这可能导致其在自然环境中觅食效率下降(Simpson *et al*, 2015)。

(2) 生理压力层面：大西洋鳕与黑线鳕(*Pollachius virens*)在地震气枪声音刺激下会出现心率降低现象(Davidsen *et al*, 2019)。间歇性高强度船舶噪声可引发沿海海洋鱼类急性应激反应，导致皮质醇浓度升高(Nichols *et al*, 2015)。此外，Mills 等(2020)发现，短期暴露于摩托艇噪声中会使雄性橙鳍双锯鱼(*Amphiprion chrysopterus*)睾酮水平升高，攻击性增强。

(3) 繁殖行为层面：交通噪声会掩盖淡水溪流雄性鱼类在繁殖期间的声学信号，干扰雌性通过声音信号识别雄性信息的能力(Holt *et al*, 2015)，且持续噪声会给厚唇弱鱼(*Argyrosomus regius*)等海洋鱼类的成功交配带来负面作用(Blom *et al*, 2019)。Brown 等(2021)野外研究发现，平鳍美洲蟾鱼(*Plainfin midshipman*)在低振幅噪声条件下会出现伦巴德效应(Lombard effect)，即提高鸣叫音量以保证交流效果。有效限制人为噪声的干扰有助于提高鱼类自然繁殖成功率。

(4) 生存能力层面：船舶噪音对鱼类成活率具有显著负面作用。船舶交通会影响海洋鱼类的活动范围，可能导致北极鳕(Ivanova *et al*, 2020)错过食物资源而影响生存。繁殖季节，摩托艇等人为噪声会干扰亲鱼护幼行为，对后代存活产生不利影响。例如珊瑚礁鱼类中的雄性安汶雀鲷(*Pomacentrus amboinensis*)，在摩托艇噪声的影响下，会增加巢内警惕行为和巢外躲避时间，这可能导致其后代生存几率降低(McCloskey *et al*, 2020)。

3　养殖环境下人为噪声对鱼类福利的影响

随着养殖活动的增加，养殖环境中的人为噪声对鱼类福利影响日益受到关注。无论是海洋、湖泊还是陆基工厂化养殖的鱼类，人为噪声均会对其生长、生理、行为和繁殖造成影响。

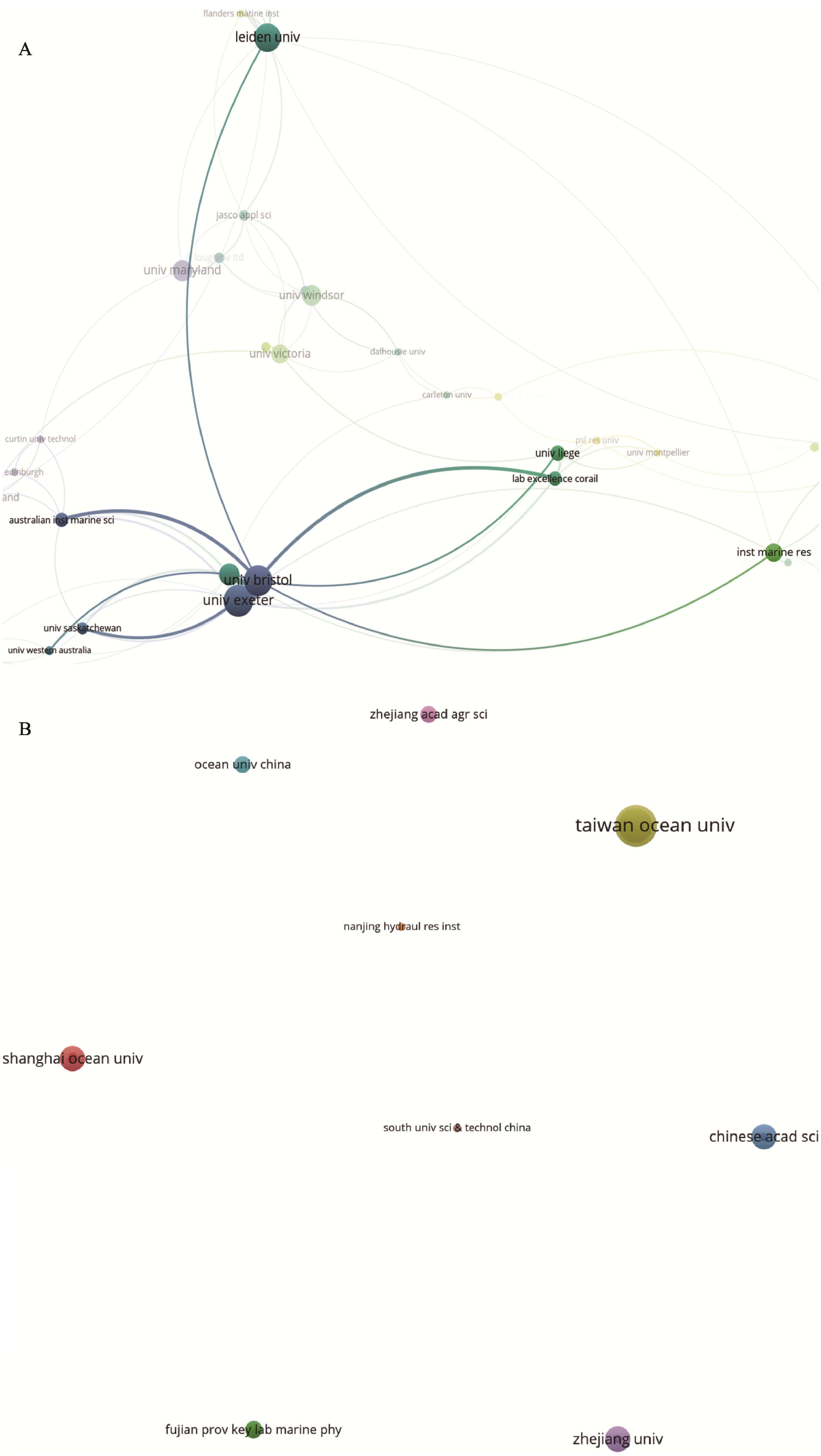

图 4　研究机构分析(A 为世界研究机构，B 为国内研究机构)

Fig.4　Research institutes analysis (A represents world research institution and B represents domestic research institution)

图 4B 中节点颜色代表机构的不同聚类。

The colors of the nodes in Fig.4B represent different clusters of institutions.

鱼类听囊在胚胎时期即开始发育，故鱼类整个发育历期都将受到养殖环境中人为噪音的影响(Jiang *et al*, 2024b)。大西洋鳕亲鱼种群在产卵期间长期暴露于养殖设施噪声后，总产卵量与受精率显著降低且胚胎成活率明显下降(Zhang *et al*, 2023a、2023b)。养殖环境中人为噪声作为一种持续性的胁迫因素，深刻影响着鱼类的生理机能。淡水养殖鱼类生理响应研究开展较早且覆盖多个鱼种，研究人员探究了鲤(*Cyprinus carpio*)、鮈(*Gobio gobio*)、河鲈(*Perca fluviatilis*)对船舶噪声的生理应激反应(Wysocki *et al*, 2006)。后续研究表明，近海养殖噪声暴露会导致金头鲷(*Sparus aurata*)幼鱼总氧化状态、溶菌酶活性、抗蛋白酶活性和白细胞水平均显著升高(Filiciotto *et al*, 2017)。RAS 水下噪声对大口黑鲈幼鱼抗氧化和免疫系统有不良影响，且低频水下噪声对其消化能力的负面影响更显著(Radford *et al*, 2019; Hang *et al*, 2021、2024)。

养殖鱼类对噪声的行为响应多体现在集体行为以及觅食行为等方面。Pieniazek 等(2020)探究船舶噪声对渔场黑鮰鲶(*Ameiurus melas*)觅食行为的影响，发现噪声导致其觅食尝试减少。作为一种具有重要商业价值的养殖鱼类，斜带石斑鱼(*Epinephelus coioides*)在水箱过滤器与水泵噪声影响下，反捕食行为的反应距离减小(Price *et al*, 2023)。Hang 等(2021)研究发现，RAS 噪声会使游动的大口黑鲈鱼群内部相邻鱼间夹角与距离增大。Zhang 等(2023a、b)进一步研究了 RAS 系统中曝气装置噪声对鱼群内部游泳行为的影响，发现噪声导致大口黑鲈的游泳行为多样性指数升高。Hang 等(2024)分析 RAS 噪声构成时指出，噪声主要集中在低频段，且低频噪声会给大口黑鲈的集体摄食行为带来严重的负面影响。

4　展望

近年来，水生动物对人为噪声响应的研究日益受到学界重视，其中针对鱼类声学及生态学的研究取得了显著进展。大量研究表明，人为噪声作为一种近年备受关注的环境胁迫因子，可通过多种途径显著影响鱼类的生理机能和行为特征，具体表现为干扰其生长发育过程、降低存活率以及损害繁殖成功率等，可能对鱼类福利构成多方面的威胁。本文通过文献计量分析法，综述了全球范围内鱼类对人为噪声响应的研究进展，并从野生鱼类与养殖鱼类两个维度展开分析，为鱼类对人为噪声响应机制的研究与发展提供了指导。随着人类活动的不断增加及集约化养殖的快速发展，未来应进一步深化人为噪声对鱼类行为及生态系统的精细化研究：(1)在关注个体行为响应的同时，更要系统揭示噪声污染对整个水生生态链的级联效应。这需要整合生物行为学、生态生理学、环境声学、流体力学等多学科理论方法，构建“个体–种群–群落–生态系统”的多尺度研究框架。同时需通过整合长期监测数据，建立覆盖不同水域的声学监测网络，结合历史数据构建噪声暴露时空数据库，追踪长期变化趋势；(2)通过生物遥测追踪噪声干扰下的生物轨迹、环境 DNA 监测噪声胁迫的种群变化，结合机器学习解析噪声参数与生物响应的关联，提升噪声生态效应的动态监测与评估能力；(3)开发基于个体、种群和生态系统的多层次模型，通过耦合声学传播模型与生态动态模型，推演噪声时空分布并量化生物响应阈值，实现噪声累积效应和长期生态影响的精准模拟；(4)推动噪声监测技术创新与养殖场景的噪声管理和应用，包括研发智能化噪声监测设备，实现噪声源自动识别、鱼类受干扰行为分析及风险预警的一体化。在水产养殖业中，既可以“变害为利”，用特定频率的声音引导鱼群定时定点聚集，提升饵料利用率，又需要“主动降噪”，为养殖设施加装消音材料，减少噪声扩散。同时，必须提高公众对鱼类声学环境需求及噪声污染危害的认知，制定科学的噪声标准和管理政策，以避免噪声对养殖鱼类福利和水下生态系统造成不可逆损害。

参考文献

贾晓平, 林钦, 蔡文贵. 大亚湾马鞭洲大型爆破对周围水域环境与海洋生物影响的评估. 水产学报, 2002, 26(4): 313–320 [JIA X P, LIN Q, CAI W G. Evaluation for the impact of large explosion at Mabianzhou Island on the neighboring aquatic environment and marine organisms in Daya Bay. Journal of Fisheries of China, 2002, 26(4): 313–320]

牛富强, 李智, 薛睿超, 等. 海上风电打桩水下噪声测量及其对大黄鱼的影响. 海洋科学, 2021, 45(8): 60–68 [NIU F Q, LI Z, XUE R C, *et al*. Impact of pile driving underwater noise from offshore wind turbines on the large yellow croaker (*Pseudosciaena crocea*). Marine Sciences, 2021, 45(8): 60–68]

王瑄, 李晓兵, 熊亚洲, 等. 水下泄洪声对草鱼幼鱼应激反应及生理损伤的影响. 湖泊科学, 2025, 37(3): 976–988 [WANG X, LI X B, XIONG Y Z, *et al*. The impact of underwater flood discharge noise on stress response and physiological injury of juvenile grass carp (*Ctenopharyngodon idellus*). Journal of Lake Sciences, 2025, 37(3): 976–988]

薛晓明, 罗刚, 李颖. 美国水产养殖业发展概况. 中国水产, 2013(10): 43–45 [XUE X M, LUO G, LI Y. General situation of aquaculture development in the United States. China Fisheries, 2013(10): 43–45]

殷雷明, 黄洪亮, 张旭光, 等. 网箱养殖大黄鱼水下声音与行为反应. 海洋渔业, 2017, 39(1): 92–99 [YIN L M, HUANG H L, ZHANG X G, *et al*. Underwater sound and behavior response of *Larimichthys crocea* in cage-culture. Marine Fisheries, 2017, 39(1): 92–99]

张博, 张旭光, 郭弘艺, 等. 上海东海大桥海上风电场水下噪声特性分析. 上海海洋大学学报, 2016, 25(4): 599–606 [ZHANG B, ZHANG X G, GUO H Y, *et al*. Characteristics of underwater noise from Shanghai Donghai Bridge offshore wind farm. Journal of Shanghai Ocean University, 2016, 25(4): 599–606]

张冬洋, 曾柏瑞. 降低水下爆破作业冲击波噪声施工技术研究. 中国水运, 2023(13): 82–85 [ZHANG D Y, ZENG B R. Research on construction technology for reducing shock wave noise in underwater blasting operations. China Water Transport, 2023(13): 82–85]

张国胜, 顾晓晓, 邢彬彬, 等. 海洋环境噪声的分类及其对海洋动物的影响. 大连海洋大学学报, 2012, 27(1): 89–94 [ZHANG G S, GU X X, XING B B, *et al*. The classification and the impact of marine environment noise on marine animals. Journal of Dalian Ocean University, 2012, 27(1): 89–94]

BADLOWSKI G A, BOYLE K S. Repeated boat noise exposure damages inner ear sensory hair cells and decreases hearing sensitivity in Atlantic croaker (*Micropogonias undulatus*). The Journal of Experimental Biology, 2024, 227(2): jeb245093

BANNER A, HYATT M. Effects of noise on eggs and larvae of two estuarine fishes. Transactions of the American Fisheries Society, 1973, 102(1): 134–136

BART A N, CLARK J, YOUNG J, *et al*. Underwater ambient noise measurements in aquaculture systems: A survey. Aquacultural Engineering, 2001, 25(2): 99–110

BLOM E L, KVARNEMO C, DEKHLA I, *et al*. Continuous but not intermittent noise has a negative impact on mating success in a marine fish with paternal care. Scientific Reports, 2019, 9(1): 5494

BRAMBELL F W R. Report of the technical committee to enquire into the welfare of animals kept under intensive livestock husbandry systems. London: Her Majesty's Stationery Office, 1965, 84

BROWN N A W, HALLIDAY W D, BALSHINE S, *et al*. Low-amplitude noise elicits the Lombard effect in plainfin midshipman mating vocalizations in the wild. Animal Behaviour, 2021, 181: 29–39

CERAULO M, SAL MOYANO M P, HIDALGO F, *et al*. Boat noise and black drum vocalizations in Mar Chiquita coastal lagoon (*Argentina*). Journal of Marine Science and Engineering, 2021, 9(1): 1–17

CRESCI A, ZHANG G S, DURIF C M F, *et al*. Atlantic cod (*Gadus morhua*) larvae are attracted by low-frequency noise simulating that of operating offshore wind farms. Communications Biology, 2023, 6(1): 353

DAVIDSEN J G, DONG H F, LINNÉ M, *et al*. Effects of sound exposure from a seismic airgun on heart rate, acceleration and depth use in free-swimming Atlantic cod and saithe. Conservation Physiology, 2019, 7(1): coz020

DAVIDSON J, BEBAK J, MAZIK P. The effects of aquaculture production noise on the growth, condition factor, feed conversion, and survival of rainbow trout, *Oncorhynchus mykiss*. Aquaculture, 2009, 288(3/4): 337–343

DE JONG K, AMORIM M C P, FONSECA P J, *et al*. Noise can affect acoustic communication and subsequent spawning success in fish. Environmental Pollution, 2018, 237: 814–823

DE JONG K, FORLAND T N, AMORIM M C P, *et al*. Predicting the effects of anthropogenic noise on fish reproduction. Reviews in Fish Biology and Fisheries, 2020, 30(2): 245–268

DUAN S S, VASCONCELOS R O, WU L L, *et al*. Managing aquaculture noise: Impacts on fish hearing, welfare, and mitigation strategies. Reviews in Aquaculture, 2025, 17(3): e70013

DUARTE C M, CHAPUIS L, COLLIN S P, *et al*. The soundscape of the Anthropocene Ocean. Science, 2021, 371(6529): eaba4658

DYNDO M, WIŚNIEWSKA D M, ROJANO-DOÑATE L, *et al*. Harbour porpoises react to low levels of high frequency vessel noise. Scientific Reports, 2015, 5: 11083

FILICIOTTO F, CECCHINI S, BUSCAINO G, *et al*. Impact of aquatic acoustic noise on oxidative status and some immune parameters in gilthead sea bream *Sparus aurata* (Linnaeus, 1758) juveniles. Aquaculture Research, 2017, 48(4): 1895–1903

FILICIOTTO F, GIACALONE V M, FAZIO F, *et al*. Effect of acoustic environment on gilthead sea bream (*Sparus aurata*): Sea and onshore aquaculture background noise. Aquaculture, 2013, 414: 36–45

GUAN S E, BROOKENS T. An overview of research efforts to understand the effects of underwater sound on cetaceans. Water Biology and Security, 2023, 2(2): 100141

GUAN S N, VIGNOLA J F, JUDGE J A, *et al*. Characterization of marine seismic survey inter-pulse sound field in an Arctic shallow-water environment. 2016 IEEE/OES China Ocean Acoustics (COA). 2016, 1–7

HALVORSEN M B, ZEDDIES D G, CHICOINE D, *et al*. Effects of low-frequency naval sonar exposure on three species of fish. The Journal of the Acoustical Society of America, 2013, 134(2): EL205–EL210

HANG S Y, ZHAO J, JI B M, *et al*. Impact of underwater noise on the growth, physiology and behavior of *Micropterus salmoides* in industrial recirculating aquaculture systems. Environmental Pollution, 2021, 291: 118152

HANG S Y, ZHU X Y, NI W Q, *et al*. Low-frequency band noise generated by industrial recirculating aquaculture systems exhibits a greater impact on *Micropterus salmoidess*.

Ecotoxicology and Environmental Safety, 2024, 272: 116074

HOLT D E, JOHNSTON C E. Traffic noise masks acoustic signals of freshwater stream fish. Biological Conservation, 2015, 187: 27–33

IVANOVA S V, KESSEL S T, ESPINOZA M, *et al*. Shipping alters the movement and behavior of Arctic cod (*Boreogadus saida*), a keystone fish in Arctic marine ecosystems. Ecological Applications, 2020, 30(3): e02050

JIANG Q H, LIANG X, YE T, *et al*. Metabonomics and transcriptomics analyses reveal the development process of the auditory system in the embryonic development period of the small yellow croaker under background noise. International Journal of Molecular Sciences, 2024a, 25(4): 1954

JIANG Q H, ZHANG Y, YE T, *et al*. Metabonomics and transcriptomics analyses reveal the underlying HPA-axis-related mechanisms of lethality in *Larimichthys polyactis* exposed to underwater noise pollution. International Journal of Molecular Sciences, 2024b, 25(23): 12610

JONES I T, D GRAY M, MOONEY T A. Soundscapes as heard by invertebrates and fishes: Particle motion measurements on coral reefs. The Journal of the Acoustical Society of America, 2022, 152(1): 399

KASTELEIN R A, GRANSIER R, MARIJT M A T, *et al*. Hearing frequency thresholds of harbor porpoises (*Phocoena phocoena*) temporarily affected by played back offshore pile driving sounds. The Journal of the Acoustical Society of America, 2015, 137(2): 556–564

LARA R A, BREITZLER L, LAU I H, *et al*. Noise-induced hearing loss correlates with inner ear hair cell decrease in larval zebrafish. The Journal of Experimental Biology, 2022, 225(7): jeb243743

LARA R A, VASCONCELOS R O. Impact of noise on development, physiological stress and behavioural patterns in larval zebrafish. Scientific Reports, 2021, 11(1): 6615

LI K, ROLLINS J, YAN E J. Web of Science use in published research and review papers 1997-2017: A selective, dynamic, cross-domain, content-based analysis. Scientometrics, 2018, 115(1): 1–20

MCCAULEY R D, FEWTRELL J, POPPER A N. High intensity anthropogenic sound damages fish ears. The Journal of the Acoustical Society of America, 2003, 113(1): 638–642

MCCLOSKEY K P, CHAPMAN K E, CHAPUIS L, *et al*. Assessing and mitigating impacts of motorboat noise on nesting damselfish. Environmental Pollution, 2020, 266: 115376

MENSINGER A F, PUTLAND R L, RADFORD C A. The effect of motorboat sound on Australian snapper *Pagrus auratus* inside and outside a marine reserve. Ecology and Evolution, 2018, 8(13): 6438–6448

MILLS S C, BELDADE R, HENRY L, *et al*. Hormonal and behavioural effects of motorboat noise on wild coral reef fish. Environmental Pollution, 2020, 262: 114250

MYRBERG A A. The effects of man-made noise on the behavior of marine animals. Environment International, 1990, 16(4/5/6): 575–586

NASH C E. The History of Aquaculture. Wiley-Blackwell, 2011

NEDELEC S L, SIMPSON S D, MORLEY E L, *et al*. Impacts of regular and random noise on the behaviour, growth and development of larval Atlantic cod (*Gadus morhua*). Proceedings of the Royal Society B: Biological Sciences, 2015, 282(1817): 20151943

NICHOLS T A, ANDERSON T W, ŠIROVIĆ A. Intermittent noise induces physiological stress in a coastal marine fish. PLoS One, 2015, 10(9): e0139157

PAYNE R, WEBB D. Orientation by means of long range acoustic signaling in baleen whales. Annals of the New York Academy of Sciences, 1971, 188(1): 110–141

PIENIAZEK R H, MICKLE M F, HIGGS D M. Comparative analysis of noise effects on wild and captive freshwater fish behaviour. Animal Behaviour, 2020, 168: 129–135

POPPER A N, CLARKE N L. The auditory system of the goldfish (*Carassius auratus*): Effects of intense acoustic stimulation. Comparative Biochemistry and Physiology Part A: Physiology, 1976, 53(1): 11–18

POPPER A N, HASTINGS M C. The effects of human-generated sound on fish. Integrative Zoology, 2009, 4(1): 43–52

PRICE N W, LIU Y, CHEN K S, *et al*. Acute noise is harmful on the anti-predator behaviour of commercially important juvenile coral reef fishes. Behavioural Processes, 2023, 210: 104908

PUIG-PONS V, SOLIVERES E, PÉREZ-ARJONA I, *et al*. Monitoring of caged bluefin tuna reactions to ship and offshore wind farm operational noises. Sensors, 2021, 21(21): 6998

RADFORD C, SLATER M. Soundscapes in aquaculture systems. Aquaculture Environment Interactions, 2019, 11: 53–62

ROBERTS L, RICE A N. Vibrational and acoustic communication in fishes: The overlooked overlap between the underwater vibroscape and soundscape. The Journal of the Acoustical Society of America, 2023, 154(4): 2708–2720

ROMAN J, ALTMAN I, DUNPHY-DALY M M, *et al*. The marine mammal protection act at 40: Status, recovery, and future of U.S. marine mammals. Annals of the New York Academy of Sciences, 2013, 1286(1): 29–49

SARÀ G, DEAN J M, DAMATO D, *et al*. Effect of boat noise on the behaviour of bluefin tuna *Thunnus thynnus* in the Mediterranean Sea. Marine Ecology Progress Series, 2007, 331: 243–253

SIDDAGANGAIAH S, CHEN C F, HU W C, *et al*. Impact of pile-driving and offshore windfarm operational noise on fish chorusing. Remote Sensing in Ecology and Conservation, 2022, 8(1): 119–134

SIDDAGANGAIAH S, CHEN C F, HU W C, *et al*. Influence of increasing noise at the offshore wind farm area on fish vocalization phenology: A long-term marine acoustical monitoring off the foremost offshore wind farm in Taiwan. Marine Pollution Bulletin, 2024, 208: 116969

SIMPSON S D, PURSER J, RADFORD A N. Anthropogenic noise compromises antipredator behaviour in European eels. Global Change Biology, 2015, 21(2): 586–593

VAN DER KNAAP I, ASHE E, HANNAY D, *et al*. Behavioural responses of wild Pacific salmon and herring to boat noise. Marine Pollution Bulletin, 2022, 174: 113257

VAN DER KNAAP I, SLABBEKOORN H, MOENS T, *et al*. Effects of pile driving sound on local movement of free-ranging Atlantic cod in the Belgian North Sea. Environmental Pollution, 2022, 300: 118913

WONG M I, LAU I H, GORDILLO-MARTINEZ F, *et al*. The effect of time regime in noise exposure on the auditory system and behavioural stress in the zebrafish. Scientific Reports, 2022, 12(1): 15353

WYSOCKI L E, DAVIDSON J W, SMITH M E, *et al*. Effects of aquaculture production noise on hearing, growth, and disease resistance of rainbow trout *Oncorhynchus mykiss*. Aquaculture, 2007, 272(1/2/3/4): 687–697

WYSOCKI L E, DITTAMI J P, LADICH F. Ship noise and cortisol secretion in European freshwater fishes. Biological Conservation, 2006, 128(4): 501–508

ZHANG X G, GUO H Y, CHEN J, *et al*. Potential effects of underwater noise from wind turbines on the marbled rockfish (*Sebasticus marmoratus*). Journal of Applied Ichthyology, 2021, 37(4): 514–522

ZHANG Y D, SHITU A, HANG S Y, *et al*. Assessing the impacts of aquaculture soundscapes on the growth, physiology and behavior of *Micropterus salmoides*. Fishes, 2023a, 8(7): 377

ZHANG Y D, SHITU A, HANG S Y, *et al*. The effects of aerator noise on the swimming, feeding, and growth of *Micropterus salmoides*. Frontiers in Marine Science, 2023b, 10: 1242793

(编辑 冯小花)

Bibliometric Analysis of Fish Responses to Anthropogenic Noise

LI Xian①, SUN Wen, SU Junjie, DUAN Shanshan, ZHANG Xiangyu, WU Lele

(*Fisheries College, Ocean University of China, Qingdao* 266003, *China*)

Abstract Anthropogenic noise generally refers to various types of noise generated by human activities and released into the environment, including mechanical operation sounds, ship navigation noises, engineering blasting sounds, and other similar acoustic emissions. As a secondary pollutant introduced into natural environments through human activities, underwater acoustic propagation characteristics and the ecological impacts of anthropogenic noise have emerged as critical interdisciplinary research focuses at the intersection of marine environmental science and aquatic biology. Unlike terrestrial environments, industrial noise in aquatic systems exhibits long-term, cumulative, and cross-habitat propagation characteristics, thereby imposing significant negative impacts on fish and other aquatic organisms in underwater ecosystems. With the acceleration of globalization, the intensity of marine development has increased exponentially. According to the Food and Agriculture Organization (FAO, 2024), the global merchant fleet tonnage has grown by 75% over the past two decades, offshore wind power capacity has expanded at an annual rate of 22%, and intensive aquaculture production now accounts for 52% of the total fishery output. The noise fields generated by these activities, ranging from ship-propeller cavitation to pile driving for offshore infrastructure and mechanical vibrations in aquaculture facilities, have significantly altered the marine soundscape. Background noise levels in some coastal waters have increased by 15–20 dB since the 1960s, driven by the cumulative effect of continuous low-frequency rumbling from shipping and intermittent high-energy pulses from construction activities. This drastic transformation of the underwater acoustic environment poses

---

① Corresponding author: LI Xian, Email: lixian@ouc.edu.cn

multidimensional stresses to fish, which rely heavily on sound for essential life processes. Physiologically, prolonged noise exposure disrupts sensory systems, causing microstructural damage to swim bladders, which are critical for sound resonance, and induces apoptosis of auditory hair cells in the inner ear, thereby impairing sound detection. Behaviorally, noise interferes with navigation, communication, and survival strategies; coral reef fish struggle with mate recognition and predator avoidance because ambient noise masks species-specific acoustic signals. At the population level, these effects cascade into a decline in local species abundance and alterations in community structure. The rapid expansion of human activities, including global shipping, offshore engineering, recreational boating, and industrial aquaculture, has brought the issue of anthropogenic noise affecting fish welfare to the forefront of attention for environmental organizations, government agencies, research institutions, aquaculture practitioners, and consumers. In recent years, the scientific community has responded to a growing body of research reflecting a heightened awareness of this ecological challenge. However, current research remains constrained by notable limitations. The majority of studies focus on single model species subjected to acute noise exposure in controlled laboratory settings, measuring short-term behavioral changes or physiological indicators, such as elevated serum cortisol. While such studies provide insights into species-specific threshold responses, there is a lack of systematic discussion from the perspective of fish habitat classification regarding the differences in responses among different ecological fish types to noise. Accordingly, this study systematically collates and analyzes a large body of relevant literature through bibliometric analysis and further employs the VOSviewer visualization tool to conduct a multidimensional quantitative analysis of 283 documents. This process constructed a keyword co-occurrence network, a national collaboration map, and an institutional distribution map, with the goal to provide visual support for interpreting research progress and outline advances in on the study of fish responses to anthropogenic noise. This study also discusses the current research status of how anthropogenic noise in natural and aquaculture environments affects fish welfare parameters such as growth, physiology, and behavior. In natural environments, fish exhibit altered swimming behaviors. For example, when ships approach, they change their swimming direction, make rapid turns, or display avoidance behaviors. Recent studies have also revealed that fish behavioral responses to anthropogenic noise extend to anti-predation and foraging activities. From a physiological perspective, intermittent high-level ship noise induces acute stress responses in coastal marine fish, manifesting as, for example, sudden increases in serum cortisol concentration. In terms of reproductive behavior, traffic noise masks the acoustic signals emitted by male fish during the breeding period in freshwater streams, disrupting the ability of females to extract information about males from these signals and negatively affecting successful mating. At the survival capacity level, ship traffic restricts the activity range of marine fish, potentially causing them to miss food resources and thus affecting their long-term survival. In aquaculture environments, fish in marine cages, lake enclosures, and land-based industrial farms are exposed to persistent anthropogenic noise. Considering recirculating aquaculture systems as an example, the low-frequency vibrations and mechanical noise generated by equipment operation have been proven to stress the growth performance and immune function of freshwater fish such as rainbow trout. The findings of this study will support public awareness, aiding in formulating guiding policies, promoting interdisciplinary development in related fields, and driving technological innovation. By unraveling the complex relationships between anthropogenic noise and fish responses, this study seeks to facilitate the coordination between human activities and the underwater soundscape environment on which fish depend for survival, improve fish welfare, and achieve a win-win situation between economic benefits and ecological sustainability.

Key words　Fish; Anthropogenic noise; Bibliometric analysis; Fish welfare