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鱼类福利的影响因素与评估方法研究进展*

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摘要 近年来,随着动物福利理念的普及与发展,其研究范畴已从陆生动物延伸至鱼类,相关议题也日益受到政府机构、动物保护组织、科研人员及水产从业者的广泛关注。栖息地环境状况、水产养殖条件、捕捞方式、市场售卖与宰杀等过程均可能对鱼类的福利需求产生显著影响。本文在概述鱼类福利概念与发展现状的基础上,归纳了影响鱼类福利的主要因素;梳理了鱼类福利的相关评价指标,包括游泳运动、摄食、攻击、集群、刻板及逃逸等行为表现,神经内分泌调控、氧化应激、免疫与血液学等类别的生理生化参数,以及其他多维综合评估方法;最后分析指出当前鱼类福利研究的局限并展望了未来的研究重点领域。本文旨在为建立标准化的鱼类福利评估框架、推动福利为导向的水产健康养殖实践提供理论依据。

关键词 鱼类福利;评价指标;应激;健康养殖

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水产养殖是人类获取优质蛋白质的重要来源。根据联合国粮农组织和经济合作与发展组织的预测,未来十年水产养殖将继续拉动全球渔业产量增长,2020—2030年间产量预计增幅达32%(FAO, 2024; SCAR, 2023; Katharios, 2019)。随着生产规模的扩张,公众对动物福利的关注日益提升。鱼类福利不仅是动物伦理议题,更关涉产业可持续发展、食品安全与生态系统健康等(Anders *et al*, 2022; 李贤等, 2025)。近年来,在水产养殖、增殖放流、休闲垂钓和实验观测等多种人为活动中,鱼类福利正持续受到环境退化、操作处理及管理策略等多方面因素的复杂影响(Cavallino *et al*, 2023)。因此,厘清这些福利影响因素,并据此建立客观、可靠的福利评价体系,已成为当前鱼类福利研究的重要任务。当前,福利评价方法主要包括:比较鱼类在自然环境和人工养殖条件下的行为

差异或不同环境下的行为表现;评估鱼类整体健康状况和生理生化响应;剖析动物的情绪状态(Galhardo *et al*, 2008)。本文旨在梳理鱼类福利的影响因素与评估方法,并指出当前鱼类福利研究中的挑战,以期鱼类福利科学理论框架的完善与生产实践提供参考。

1 鱼类福利研究现状概述

自20世纪中期以来,动物福利逐渐成为重要的社会与学术议题,并在理论上被界定为一个多维概念(Barreto *et al*, 2022; Broom, 1991)。Broom (1986)将动物福利定义为“个体对其环境适应能力的状态”,当适应能力受限时福利下降,这为后续的福利量化研究奠定了概念基础。为系统评估动物的福利状况,Mellor 等(2020)提出了包括营养、环境、健康、行为

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及心理状态五个相互关联维度的“五域模型”。这与农场动物福利委员会(Farm Animal Welfare Council, FAWC)提出的五项自由原则一脉相承,即必须确保动物享受不受饥渴的自由,享受生活舒适的自由,享受不受痛苦、伤害和疾病的自由,享受生活无恐惧和无悲伤的自由,享受表达天性的自由,以保障其福利(Broom, 2007),以上观点共同构成了现代动物福利科学的核心理念。

值得关注的是,长期以来动物福利研究的重点主要集中于陆生禽畜动物,直到近年来鱼类福利才逐渐受到重视(Barreto *et al*, 2022)。20世纪90年代,鱼类福利(Fish welfare)由世界农场动物福利协会(Compassion in World Farming, CIWF)首次提出(Lymbery, 1992)。目前,其概念可以理解为:鱼类在健康、舒适与安全的环境中,获得充足营养并免受疼痛、恐惧与压力的良好生存状态(李贤等, 2025)。造成这一滞后的原因,一方面是关于“鱼类是否具备痛苦/疼痛等意识体验”以及“是否应获得与哺乳动物和家禽同等福利考量”的争议持续存在(Huntingford *et al*, 2006、2014);另一方面,鱼类的物种多样性与水生场景的观测难度也提高了评估与干预的门槛(Huntingford *et al*, 2014)。如今,越来越多的神经生物学、行为学及生理学证据表明,鱼类拥有复杂的感知能力,具有痛苦/疼痛的意识体验,这为生产和研究过程中实施福利改善措施提供了科学依据(Huntingford *et al*, 2006; Saraiva *et al*, 2024)。

目前,国际鱼类福利研究聚焦于识别和解析各类影响因素及其内在关联,探明科学的评价指标体系以服务于生产实践。在福利影响因素方面,研究表明多种生产环节构成福利压力源,涵盖养殖阶段的放养密度、饲料营养与疾病防治(Carbonara *et al*, 2020; Hatzilygeroudis *et al*, 2023; van den Boogaart *et al*, 2023),操作与流通环节的捕捞、分级、活体运输及宰杀方式(Refaey *et al*, 2018; Aya *et al*, 2023; Saraiva *et al*, 2024),以及外部环境胁迫如水温不适、低氧与水体污染等(Pedrazzani *et al*, 2022; Shahjahan *et al*, 2022)。在福利评价指标体系方面,已由早期依赖生长速率与死亡率等生产性能指标(Veldhuizen *et al*, 2018),发展为运用生理生化指标(Paschke *et al*, 2018; Yang *et al*, 2024)、行为学指标(Barreto *et al*, 2022)、健康指标(Weirup *et al*, 2021)以及一些新兴综合框架(Browning, 2023; Alvarado *et al*, 2025)。近年来,基于神经内分泌、氧化应激、黏膜免疫等分子与细胞层面的生物标志物研究(Kumar *et al*, 2019; Pérez-Sánchez *et al*, 2013),也为开发更具前景的鱼类福利评估工具提供了重要支

撑。此外,研究者还强调实验室条件下的福利指标(Laboratory-based Welfare Indicators, LABWIs)与现场操作福利指标(Operational Welfare Indicators, OWIs)的匹配度与一致性(Kristiansen *et al*, 2020),这推动了用于生产实践的福利评估工具的开发,例如用于鱼类养殖与捕捞的福利核查的开放线上数据库 Fair-fish database (Maia *et al*, 2025a)、鲑鱼福利指数模型(Salmon Welfare Index Model, SWIM) (Stien *et al*, 2013)等。在福利立法与标准方面,21世纪初,世界动物卫生组织(World Organization for Animal Health, WOAH)发布了动物福利标准,将动物福利(含鱼类)纳入战略重点(Lund *et al*, 2007),并于2008年将水生动物福利写入《水生动物卫生法典》,覆盖运输与宰杀等环节(李文翰等, 2025a);欧洲食品安全局(European Food Safety Authority, EFSA)在2004—2009年发布了关于养殖鱼类捕捞、运输、致晕、宰杀以及养殖系统的报告,强化了作业节点与指标证据的对接(EFSA, 2008、2009);挪威动物保护法(Norwegian Animal Protection Act)、挪威动物福利法(Norwegian Animal Welfare Act)和新西兰动物福利法(New Zealand Animal Welfare Act)等(Kristiansen *et al*, 2020)也相继出台。

我国鱼类福利研究起步相对较晚,现有研究大多集中于鱼类养殖的福利问题以及对健康养殖的探索。例如,有学者关注养殖密度对草鱼(*Ctenopharyngodon idella*)、翘嘴鲌(*Siniperca chuatsi*)等鱼类的影响(陆可等, 2023; 李文翰等, 2025b),养殖水质对黑鲷(*Sebastes schlegelii*)和大口黑鲈(*Micropterus salmoides*)的影响(Li *et al*, 2023; 金渝钦等, 2025),以及环境丰容对大泷六线鱼(*Hexagrammos otakii*)和黑鲷(Zhang *et al*, 2022)的影响。此外,生产相关情境(如噪音、振动刺激、投喂频率、空气暴露等)对特定鱼类生理生化应激响应的影响也得到初步探讨,涉及珍珠龙胆石斑鱼(*Epinephelus fuscoguttatus* ♀×*E. lanceolat* ♂) (杨仕沛等, 2024)、大黄鱼(*Larimichthys crocea*) (叶林昌等, 2023)、黑鲷(*Acanthopagrus schlegelii*) (朱越等, 2020)、美洲鲈(*Alosa sapidissima*) (张勇等, 2016)、大口黑鲈(Hang *et al*, 2021)等鱼类。总体而言,目前我国鱼类福利研究多侧重于对单一或少数实际问题的个案分析,尚未形成明晰的福利评估方法体系(李贤等, 2025)。在法规建设方面,我国涉及鱼类保护的立法和标准包括《中华人民共和国渔业法》、《中华人民共和国水生野生动物保护实施条例》、《中华人民共和国野生动物保护法》、《实验动物管理条例》、《关于善待实验动物的指导性意见》等,但内容多限于捕捞、驯养、饲料

及用药等范畴,与发达国家相比,我国在该领域的法规建设整体滞后(林金杏等, 2012; 刘俊荣等, 2024; 李文翰等, 2025a)。这种研究体系与法规建设的不足,不仅制约了相关立法与实践的进程,也凸显了加强基础研究、推动学科体系化建设的重要性和迫切性。

2 鱼类福利的影响因素

2.1 生物间相互作用

个体间竞争与捕食等相互作用是构成鱼类福利的重要内因。鱼类社会等级制度形成过程中,为确立优势地位而表现出高度的攻击与对抗性互动(Gauy *et al.*, 2019; Cavallino *et al.*, 2023)。优势个体在争夺食物、配偶与领地过程中直接攻击或反复威胁从属个体(Martins *et al.*, 2012)。长期的社会压力通常会引发从属个体出现显著的行为与生理变化,包括活动水平下降、摄食减少、攻击性减弱、体色改变以及血浆皮质醇水平升高等(Martins *et al.*, 2012)。不仅如此,从属个体还表现出显著的生长抑制现象,其机制可能涉及生理应激加剧、食物获取比例失调及代谢限制(Overton *et al.*, 2010; Batzina *et al.*, 2018; Dikel *et al.*, 2020)。此外,配偶匹配质量是影响鱼类情绪状态与繁殖成功的重要因素。对于求偶行为复杂或亲代抚育期较长的物种,其行为若受到抑制,也会导致亲代和幼体福利状况不佳(Chiang *et al.*, 2024)。Laubu 等(2019)对橘斑孳丽鱼(*Amatitlania siquia*)的研究发现,雌鱼与其偏好的雄鱼配对后表现出产卵更早、护卵时间更长、攻击行为减少以及后代数量更多;相反,与其非偏好的雄鱼配对后则呈现出消极情绪状态,繁殖成效也显著降低。除种内选择压力外,捕食等种间相互作用同样也是影响鱼类福利的关键生物因素。捕食者的存在本身即可对猎物鱼类构成胁迫;即使未发生实际捕食行为,此类“捕食风险”仍会诱发猎物的觅食与活动水平下降、避难所使用增加等反捕食行为(Lönnstedt *et al.*, 2013; Brown *et al.*, 2016)。例如,在捕食者-猎物混养体系中,大龙六线鱼对黑鲷的生长与生理状态产生显著抑制:前者在受惊扰或争食时引发黑鲷群体骚乱,并通过高频种间攻击与资源竞争,直接导致后者体重及特定生长率下降,同时伴随能量消耗加剧与生理应激水平上升(Zhang *et al.*, 2022)。

2.2 栖息/养殖环境

2.2.1 栖息地状况 人类活动正持续重塑鱼类的栖息环境,水下噪声、航运以及环境富集等均影响鱼类福利水平。航运、海洋工程与水产养殖等活动产生

的噪声可干扰鱼类的交流、觅食与运动行为,工业化循环水养殖系统中的环境噪声可对幼年大口黑鲈的抗氧化与免疫系统造成负面影响,并扰乱其正常游泳模式(Hang *et al.*, 2021)。船舶通行引发多种物理干扰,如大浪、沉积物再悬浮、湍流、水流逆转及近岸区域裸露(Liedermann *et al.*, 2014; Gabel *et al.*, 2017),导致沿岸鱼类产卵、孵化与育幼阶段所依赖的环境条件极大改变(Zajicek *et al.*, 2019)。为应对栖息地退化的不良效应,通过增加环境异质性(如设置碎石、砂砾、遮蔽物等)的环境丰富有助于提升鱼类的认知能力,降低应激水平与能量消耗、减少种内攻击与体表损伤及疾病发生率(Näslund *et al.*, 2014; 曾足仙等, 2025),其成效在金头鲷(*Sparus aurata*)、虹鳟(*Oncorhynchus mykiss*)以及尼罗罗非鱼(*Oreochromis niloticus*)等鱼类的环境富集实验中得到验证(Tatemoto *et al.*, 2021; Brunet *et al.*, 2022; Cabrera-Álvarez *et al.*, 2024)。例如,长期处于贫乏环境中的尼罗罗非鱼表现出更多的冻结行为(freezing behavior, 静止不动的警戒状态)与恐惧反应,而环境丰富条件下的个体则展现出更高的探索性与较低的恐惧水平(Tatemoto *et al.*, 2021)。

2.2.2 水质条件 水质恶化是影响鱼类福利最直观的因素(Pedrazzani *et al.*, 2022)。水体中温度、溶解氧(dissolved oxygen, DO)、pH、盐度与污染负荷的异常波动构成非生物胁迫。其中,温度是影响鱼类等水产动物生存、繁殖、分布及生活史最关键的生物因子之一(Xia *et al.*, 2021)。即使在物种耐受范围内,温度的非正常波动也会引发代谢变化,影响摄食、呼吸和生长速度(Pedrazzani *et al.*, 2022)。低浓度 DO 可诱发鱼类氧化应激并损害免疫系统,增加疾病风险;而长期处于高浓度 DO 环境也可能因活性氧(reactive oxygen species, ROS)过度积累引发氧化损伤(Menon *et al.*, 2023)。盐度及酸碱度的极端变化可导致离子平衡失调、生理代谢紊乱、行为异常及组织功能受损(Ordóñez-Grande *et al.*, 2020; van Rijn *et al.*, 2021; Li *et al.*, 2023; Chen *et al.*, 2025)。重金属及氨氮的累积不仅引发鱼类的氧化应激和生理毒性,还导致鳃、肝和肾等重要组织损伤,干扰机体免疫调节与细胞稳态(Al-Ghanim *et al.*, 2019; Xu *et al.*, 2021; Shahjahan *et al.*, 2022)。此外,微塑料作为一种全球性新兴污染物也对渔业生产造成重要影响,其污染可导致鱼类行为异常、生长发育迟缓、疾病易感性上升和死亡率增加(Foley *et al.*, 2018)。

2.2.3 养殖密度 养殖密度是影响水产养殖鱼类福利最常见的因素(Carbonara *et al.*, 2020)。高密度养殖通常会对鱼类产生不利影响,但最适密度的确定尚

存争议。例如,高密度可诱发黑鲟明显的攻击与同类相食行为,同时伴随 5-羟吲哚乙酸(5-HIAA)/5-羟色胺(5-HT)比值及皮质醇水平显著升高(Li *et al*, 2022);然而,对尖齿胡鲶(*Clarias gariepinus*)的研究发现,低密度也会诱发攻击行为并增加皮肤损伤率(van de Nieuwegiessen *et al*, 2008)。此外,对虹鳟的研究发现,低密度 12 kg/m³ 与高密度 17 kg/m³ 养殖并未对其生长、行为与应激生理指标(如皮质醇、葡萄糖、乳酸等)造成显著不利影响(Carbonara *et al*, 2020)。适宜养殖密度的确定既要考虑养殖环境容纳量,又要关注物种本身的生物学特性,未来研究明确养殖密度阈值对于兼顾鱼类福利与生产绩效的平衡具有重要意义。

2.2.4 营养供给 鱼类的整体性能和抗病能力高度依赖于科学的营养供给与饲喂制度(Oliva-Teles, 2012)。营养供给不足会加剧群体内社会竞争并直接损害个体福利(Noble *et al*, 2018)。例如,大西洋鲑(*Salmo salar*)在饥饿时表现出更高的攻击性,显著增加群体争斗频率(van den Boogaart *et al*, 2023)。饵料充足且空间分散的投喂可有效缓解竞争,使更多能量用于生长,从而可提升鱼类福利水平与生产效率(Oikonomidou *et al*, 2019)。此外,富含天然免疫刺激成分的功能性饲料被视为增强鱼类免疫力和适应性的潜在策略(Marmelo *et al*, 2024)。此类饲料既可满足鱼类基本营养需求,又可改善其免疫状态,促进健康与最佳功能表现。例如,掌状海带(*Laminaria digitata*)的多糖提取物具有免疫调节和抗氧化作用,将其添加于饲料后投喂金头鲷可增强其免疫功能(Marmelo *et al*, 2024)。在饲喂制度上,使投喂时间与频率符合鱼类自然摄食节律可避免不良福利影响。例如,对大口黑鲈的研究表明,每日 3 次比 2 次投喂下生长更快(周刚等, 2025)。合理的投喂频率还能减少残饵与代谢废物,降低环境负荷及养殖成本(杨仕沛等, 2024)。

2.2.5 疾病与防治 疾病是影响鱼类健康与福利的关键因素,主要由寄生虫、病毒、细菌和真菌等病原体引起(Elgendy *et al*, 2024)。寄生虫感染分为体外寄生(如单殖吸虫、桡足类蚤和等足类鱼虱)与体内寄生(如肠黏孢子虫 *Enteromyxum leei* 和肠孢子虫 *Enterospora nucleophila*) (Rigos *et al*, 2024),可导致组织损伤、体重下降、生长迟缓、抵抗力下降和死亡(唐嘉嘉等, 2020; Hatzilygeroudis *et al*, 2023)。常见病毒性疾病包括传染性造血坏死病毒(IHNV)、病毒性出血性败血症病毒(VHSV)和罗非鱼湖病毒(TiLV)等(Magnadottir, 2010; Roy *et al*, 2021),感染后鱼体常表现为底栖静止、异常游泳及体表出血等症状

(Hatzilygeroudis *et al*, 2023)。细菌性疾病在水产养殖中发生频率较高,由气单胞菌属(*Aeromonas*)、假单胞菌属(*Pseudomonas*)、弧菌属(*Vibrio*)及爱德华氏菌属(*Edwardsiella*)等致病菌引起,症状包括皮肤溃疡、鳍尾腐烂和眼球肿胀等(Hatzilygeroudis *et al*, 2023; Hegde *et al*, 2023)。真菌病原以水霉属(*Saprolegnia*)、青霉属(*Penicillium*)、曲霉属(*Aspergillus*)等为主(Gozlan *et al*, 2014; Mahfouz *et al*, 2019; Hatzilygeroudis *et al*, 2023),典型症状包括眼球突出,皮肤、鳍或鳃组织出现白色、灰色、棕色或绿色的霉斑(Steckler *et al*, 2014; Hatzilygeroudis *et al*, 2023)。在水产养殖中,传统依赖化学药物的疾病防控方式因耐药性、药物残留及环境毒性等问题受到限制,正逐渐被疫苗、益生菌及植物提取物等绿色综合防控策略取代(Elgendy *et al*, 2024)。

2.3 生产过程

2.3.1 遗传选育 人为干预鱼类遗传特性与生殖过程的操作有助于提升生产效率,但同时也对鱼类健康与福利构成潜在威胁。例如,对大西洋鲑施加三倍体诱导虽可获得较高的三倍体率,但常伴随染色体异常,导致生长性能下降及疾病易感性升高(Glover *et al*, 2020);三倍体鲑鱼普遍存在骨骼与心脏畸形、白内障和皮肤溃疡等问题,且对环境变化与管理应激的耐受性也显著降低(Fraser *et al*, 2015; Fonseka *et al*, 2022)。在鱼类性别诱导方面,外源激素处理虽能有效诱导单性群体,但也可能对鱼体造成副作用。例如,泰国斗鱼(*Betta splendens*)经激素处理后,成鱼阶段出现精子数量与活力下降,并伴随交配行为异常(Kirankumar *et al*, 2002);鲤鱼(*Cyprinus carpio*)在高浓度或长时间激素浸泡下,虽雄性化比例提高,但孵化率与鱼苗存活率显著降低(Asad *et al*, 2021)。在人工繁殖过程中,常需挤压亲鱼腹部迫使其排出配子,该操作易导致强烈的应激反应,并伴随体表或内部组织损伤的风险。基于鱼类福利视角,欧洲食品安全局(EFSA)建议在麻醉条件下实施温和操作以最大限度降低鱼类应激,对某些鲑鱼可采用“单次采精后立即宰杀”的方式以减少重复操作对福利的负面影响(Giménez-Candela *et al*, 2020)。

2.3.2 捕捞与分级 捕捞与分级是渔业水产常见管理操作,其中存在的鱼类福利问题容易被忽视。围网作为常见的捕捞方式,在作业过程中常因拥挤与缺氧诱发鱼类急性应激(Anders *et al*, 2021, 2022),而野生鱼在捕获后转入人工密集养殖更易出现福利受损(Chandararathna *et al*, 2021)。因此,有必要根据物种

特性开发适宜的操作技术。Chandararathna 等(2021)系统总结了在不同鱼类中所采用的捕捞、恢复及养殖技术实践,为优化流程提供了指导。此外,鱼类规格分级可形成体型均匀的群体,便于管理,并可能减少因体型差异引起的攻击行为(Huntingford *et al*, 2014)。然而,分级过程中的搬运和离水处理会导致强烈应激及皮肤破损、鳞片脱落等机械损伤(Huntingford *et al*, 2014; Giménez-Candela *et al*, 2020)。值得注意的是,分级对鱼类生长的影响尚无一致结论(Dikel *et al*, 2020)。例如,体型分级虽可促进太平洋短鳍鳗(*Anguilla bicolor pacifica*)特定规格个体的生长,但未改善其黄鳗阶段的整体表现(Aya *et al*, 2023);而在欧洲海鲈(*Dicentrarchus labrax*)中,分级对生产性能无显著影响(Batzina *et al*, 2018)。鉴于研究结果不一致,Overton 等(2010)建议以能否在生产中提升群体生长性能作为分级的先决条件。

2.3.3 活体运输 活体运输分为运输前处理和运输过程两个阶段(Refaey *et al*, 2018)。运输前处理包括追逐、捕捞、分拣、空气暴露及包装等操作,而运输过程则涉及高密度装载、长时间运输、摇晃、震动与噪声干扰等多种胁迫因素(Refaey *et al*, 2018; Cockrem *et al*, 2019; Wang *et al*, 2024)。这些操作和环境变化均会干扰鱼类正常的生理状态,可诱发强烈的应激反应,严重时甚至导致鱼类死亡。研究表明,空气暴露可导致鱼体肝糖原消耗,皮质醇、葡萄糖、乳酸、蛋白质及血浆甘油三酯等水平升高,并伴随挣扎反应和呼吸加快等(张勇等, 2016; Cockrem *et al*, 2019)。在包装和运输方面,随着运输时长导致氨氮浓度升高、DO 浓度和 pH 下降(Refaey *et al*, 2018; Wang *et al*, 2024),水体环境恶化损害鱼类生理功能、降低对病原体的抵抗能力、扰乱正常代谢并降低存活率(Liu *et al*, 2016; Refaey *et al*, 2017)。在模拟船运条件下,多种物理胁迫也会引发鱼类应激反应。例如,长时间摇晃会导致黑鲷幼体存活率下降(朱越等, 2020);低频震动可引起大黄鱼肾上腺素和甲状腺素浓度上升(叶林昌等, 2023);低频噪声使珍珠龙胆石斑鱼肾上腺素、促肾上腺皮质激素和 5-羟色胺等指标上升(刘滨等, 2020)。由此可见,优化活体运输各环节操作、规范运输装备并尽可能缩短运输时间,是缓解运输胁迫、保障鱼类健康与福利的重要措施。

2.3.4 市场售卖 市场售卖(包括活鱼交易、观赏鱼与湿货市场等)同样存在系列鱼类福利风险,但目前鲜有相关报道。在售卖环节,鱼类通常需经历运输后的再次高密度暂养、频繁挑拣或转移,并长期滞留于水质与温度波动较大的环境中,从而诱发神经内分泌紊

乱及呼吸代谢失衡等应激反应。市场暂养池中的高密度环境、低 DO、高氨氮以及不当的混养方式(如捕食者和猎物鱼混养)等,均可能提高鱼类应激水平与疾病易感性并影响鱼肉品质。此外,在食用鱼零售中,部分物种以活鱼形式出售,其在销售与交易过程中常经历粗暴搬运、长时间震荡甚至离水运输等情况,Cooke (2016)建议劝阻零售商销售活鱼或建立科学的操作流程。另有研究者指出,将观赏鱼捞出水面、不戴防护手套与其鱼体接触,可损害鱼体的保护性黏液层和鳞片,并且运输中水流晃动引发的机械干扰,进一步提高应激水平导致健康损害(Maia *et al*, 2025b)。这些发现为市场售卖环节中鱼类福利的保护与研究提供了参考。

2.3.5 宰杀操作 宰杀操作不仅影响鱼类福利水平而且影响最终肉质品质。目前常用的鱼类宰杀方法包括窒息、电击、气体混合、敲击头部、脊髓穿刺和低温致死等(刘俊荣等, 2024; Yang *et al*, 2024)。不适当的宰杀操作会引起鱼类强烈的应激反应,导致其渗透调节、酶活性、新陈代谢及血液成分改变(Wang *et al*, 2021; Mercogliano *et al*, 2024; Yang *et al*, 2024),进而诱发水分流失、僵直、脂质氧化、pH 下降和蛋白质变性等问题,严重影响肉质(Wang *et al*, 2021; 吴燕燕等, 2023; Saraiva *et al*, 2024)。例如,敲击致昏可显著降低鲤鱼血液皮质醇与葡萄糖水平,并提高肌肉保水性;而窒息法则导致极高应激水平与严重汁液流失(Daskalova *et al*, 2016)。虹鳟在空气窒息中肌肉僵直、全程清醒并承受超过 20 min 的剧烈痛苦(Saraiva *et al*, 2024)。相比头部敲击、脊髓穿刺、CO₂ 或混合气体窒息等方法,低温致死会使尼罗罗非鱼皮质醇水平显著升高且致死时间延长(Yang *et al*, 2024)。在鱼类宰杀过程中,致晕效果不佳是关键的福利风险源。头部敲击和电击致晕是最常用的两种方法,敲击易因位置偏差或力度不足失效,而电击常因电流过低仅致麻痹而非完全晕厥(Cooke, 2016)。因此,鱼类宰杀相关的致晕和宰杀等设备应定期检测,若致晕失败或鱼类恢复意识,应立即补充致晕(Mercogliano *et al*, 2024)。总体而言,理想的人道宰杀应以最大限度地降低鱼体应激和痛感(刘俊荣等, 2024),坚持“低应激、高效率”原则。

3 鱼类福利的评估方法

3.1 行为学评价体系

鱼类行为是评估其福利的重要指标。作为一种非侵入式方法,行为指标具有快速且易于观察的优势,

可揭示潜在的福利问题并有助于提出改善措施,因此被作为核心指标广泛用于鱼类福利与健康评价(Martins *et al.*, 2012; Carbonara *et al.*, 2020; Oliveira *et al.*, 2024a)(表 1)。

游泳、攻击、摄食、集群和呼吸等行为属于与功能性需求紧密相关的指标,通常与急性和慢性应激源相关,可作为鱼类福利水平的判定依据(Martins *et al.*, 2012)。活跃性、探索性、攻击性与集群行为等既是鱼类个性特征的重要体现,也是评估其在养殖环境下福利状态的关键指征(van de Nieuwegiessen *et al.*, 2008; Martins *et al.*, 2012)。具体而言,活跃性、探索性与攻击性常用于反映鱼类的日常状态与应激程度(Arechavala-Lopez *et al.*, 2020; Carbonara *et al.*, 2020; Li *et al.*, 2022; Zhang *et al.*, 2025)。鱼类集群行为受群体规模的影响,低密度群体的个体往往表现得更加胆怯,这可能源于其捕食警觉性增强,而较大群体则有助于缓解此类焦虑状态(Saxby *et al.*, 2010; Martins *et al.*, 2012)。鱼类呼吸水平、刻板与逃逸等则直接反映个体的情绪状态与环境适应性(Martins *et al.*, 2012)。在遭遇环境胁迫时,鱼类常表现为底栖静止、水面呼吸、呼吸频率加快及逃逸等行为增强(van de Nieuwegiessen *et al.*, 2008);而在持续单调环境、空间限制或病原感染等慢性应激条件下,则易出现刻板行为(van de Nieuwegiessen *et al.*, 2008; Martins *et al.*, 2012; Khalil *et al.*, 2018)。尽管行为指标具有重要福利评估价值,其实际应用中仍存在问题:其一,正常与异常行为以及人工环境下正常行为与野外自然行为之间的界限往往难以界定;其二,同一种行为在不同群体间可能存在差异;其三,行为具有较强的时空动态性,量化难度大(Saxby *et al.*, 2010; Martins *et al.*, 2012)。为实现更科学的福利评估,亟需优化行为学评价指标体系并建立鱼类行为-福利评价标准。

3.2 生理生化评价体系

鱼类福利评价的生理生化指标以应激反应理论框架为基础,通过多层级指标体系反映其在外界应激源作用下的健康状况。该框架包含三个递进层级(图 1):初级反应表现为应激激素(如儿茶酚胺、皮质醇等)向循环系统的迅速释放;次级反应由上述激素触发,具体表现为心率和呼吸频率加快,并动员能量代谢物以满足机体需求等;若胁迫持续存在,将发展出三级反应,最终导致能量储备耗竭、免疫功能抑制、生长迟缓与性成熟受阻,甚至个体死亡(Barton, 2002; Jerez-Cepa *et al.*, 2021)。在鱼类福利评价中,神经内分泌调控、氧化应激、免疫调节和血液学指标的变化等是反映其福利状况的重要方面(表 2)。

在神经内分泌调控中,皮质醇是下丘脑-垂体-肾间轴(Hypothalamus-Pituitary-Interrenal axis, HPI axis)的最终产物,是评估内分泌应激的关键生物标志物(Carbajal *et al.*, 2019; Sadoul *et al.*, 2019; Lemos *et al.*, 2023),其水平升高可指示急性或慢性压力负荷(Carbajal *et al.*, 2019; Lemos *et al.*, 2023)。除激素外,神经毒性同样可反映环境胁迫的影响。乙酰胆碱酯酶(Acetylcholinesterase, AChE)活性是最常用的神经毒性指标,其抑制常由金属、农药或药物暴露引起(Kumar *et al.*, 2019; Uçar *et al.*, 2022),导致神经递质乙酰胆碱积累,进而引发行行为异常(Formicki *et al.*, 2025)。神经内分泌激素与神经毒性指标的联合分析,有助于揭示鱼类应激反应从信号传导到行为改变的多层机制。

氧化应激作为应激反应的核心环节,由高温、低氧、污染物等胁迫因子诱发,导致活性氧(ROS)累积并破坏细胞稳态(Andrade *et al.*, 2015; Menon *et al.*, 2023)。在正常条件下,抗氧化防御系统通过酶促与非酶促机制维持 ROS 平衡(Rani *et al.*, 2019),一旦失衡即发生氧化应激(Birnie-Gauvin *et al.*, 2017; Rani *et al.*, 2019),造成蛋白质、脂质与 DNA 氧化损伤,抗氧化系统(Antioxidant system, AOS)的活性也会发生变化,并进一步扰动细胞代谢与调控网络(Lushchak, 2016; Melkonyan *et al.*, 2024; Grădinariu *et al.*, 2025),从而影响鱼类福利水平并导致生长与繁殖性能下降(Menon *et al.*, 2023)。常用评估指标包括丙二醛(MDA)、硫代巴比妥酸反应物质(Thiobarbituric acid reactive substances, TBARS)(Melkonyan *et al.*, 2024; Oliveira *et al.*, 2024b)、蛋白质巯基(Protein thiol groups, PTG)、羰基(Protein carbonyl groups, PCG)(Florescu *et al.*, 2021)以及抗氧化酶如过氧化氢酶(Catalase, CAT)、超氧化物歧化酶(Superoxide dismutase, SOD)和谷胱甘肽还原酶(Glutathione reductase, GR)等(Rani *et al.*, 2019; Melkonyan *et al.*, 2024)。

免疫与血液学反应是实现从局部到全面评估鱼类生理健康的重要手段。皮肤黏液由黏膜上皮细胞分泌,含有黏蛋白、免疫球蛋白(IgM 和 IgT)、溶菌酶及抗菌肽等活性物质,构成抵御外界威胁的第一道防线(Salinas, 2015; Reverter *et al.*, 2018)。其功能受损将增加病原入侵风险,威胁鱼体健康并降低福利水平(Sanahuja *et al.*, 2023)。研究表明,黏膜与血浆中 IgT/IgM 比值是反映黏膜免疫的首个指标(Salinas, 2015),而溶菌酶、酯酶等酶活性也可用于应激评估(Reverter *et al.*, 2018)。血液学与血清生化指标也是常用的生理评估手段(Peres *et al.*, 2015; Fazio, 2019)。典

表 1 鱼类福利评价的行为学指标
Tab.1 Behavioural indicators in fish welfare evaluation

行为学指标 Behavioural indicators	行为描述 Behaviour description	测量指标 Measurement indexes	影响因素 Influence factors	物种 Species	参考文献 References
活跃性 Activity	鱼类的日常活动水平	游泳运动的速度、加速度及频率等	养殖密度、溶氧	虹鳟(<i>O. Mykiss</i>) 大西洋鲑鱼(<i>G. morhua</i>) 大西洋庸鲽(<i>H. hippoglossus</i> L.)	Kristiansen <i>et al.</i> , 2004; Herbert <i>et al.</i> , 2005; Carbonara <i>et al.</i> , 2020
探索性 Exploration	鱼类为探索和收集周围新异环境信息而呈现的行为	探索新异物体空间的行为 频次、距离	环境丰富度	金头鲷(<i>S. aurata</i>) 西德鲟(<i>Acipenser ruthenus</i> L.)	Arechavala-Lopez <i>et al.</i> , 2020; Fazekas <i>et al.</i> , 2023
攻击性 Aggressiveness	鱼类为获得食物、领地、配偶等资源的侵略性活动	追逐、撕咬、推挤等行为发生频次	养殖密度、社会等级、投喂方式、环境丰富度	金头鲷(<i>S. aurata</i>) 欧洲海鲈(<i>D. labrax</i>) 尖齿胡鲶(<i>C. gariepinus</i>) 黑鲟(<i>S. schlegelii</i>) 巴拉那河丽体鱼(<i>Cichlasoma paranaense</i>)	Gauy <i>et al.</i> , 2019; Oikonomidou <i>et al.</i> , 2019; Li <i>et al.</i> , 2022; Ojelade <i>et al.</i> , 2022
集群行为 Collective behaviour	鱼类同步调且同向的群体游泳	群游时间、相邻指数	群体规模、环境丰富度	尖齿胡鲶(<i>C. gariepinus</i>) 神仙鱼(<i>P. scalare</i>) 霓虹脂鲤(<i>P. innesi</i>) 白云山波鱼(<i>T. albonubes</i>) 虎皮鱼(<i>B. tetrazona</i>)	Saxby <i>et al.</i> , 2010; Ojelade <i>et al.</i> , 2022
呼吸频率 Respiratory rate	鱼类通过口腔与鳃盖运动调节水流经鳃的频率	鳃盖运动的频次	养殖密度、溶氧、病原体感染	尖齿胡鲶(<i>C. gariepinus</i>) 尼罗罗非鱼(<i>O. niloticus</i>)	van de Nieuwegiessen <i>et al.</i> , 2008; Khalil <i>et al.</i> , 2018
摄食行为 Feeding behaviour	鱼类在搜寻、选择及摄取食物过程中的一系列行为活动	持续时间、摄食量、觅食频率	营养供给、水体更换率	金头鲷(<i>S. aurata</i>) 尼罗罗非鱼(<i>O. niloticus</i>)	Martins <i>et al.</i> , 2009; Oliveira <i>et al.</i> , 2024a
刻板行为 Stereotypic behaviour	鱼类重复、不变且没有明显目标或功能的行为状态	圆周运动、垂直运动等强迫性游动的频率和持续时间	环境丰富度、养殖密度、病原体感染	尖齿胡鲶(<i>C. gariepinus</i>) 尼罗罗非鱼(<i>O. niloticus</i>)	van de Nieuwegiessen <i>et al.</i> , 2008; Khalil <i>et al.</i> , 2018
逃逸行为 Escape behaviour	鱼类应对不适环境的快速逃逸表现	爆发游泳频次、跳跃出水频次	养殖密度、环境丰富度、抓捕刺激	金头鲷(<i>S. aurata</i>) 虹鳟(<i>O. Mykiss</i>) 尖齿胡鲶(<i>C. gariepinus</i>)	van de Nieuwegiessen <i>et al.</i> , 2008; Oliveira <i>et al.</i> , 2024a; Saraiva <i>et al.</i> , 2024

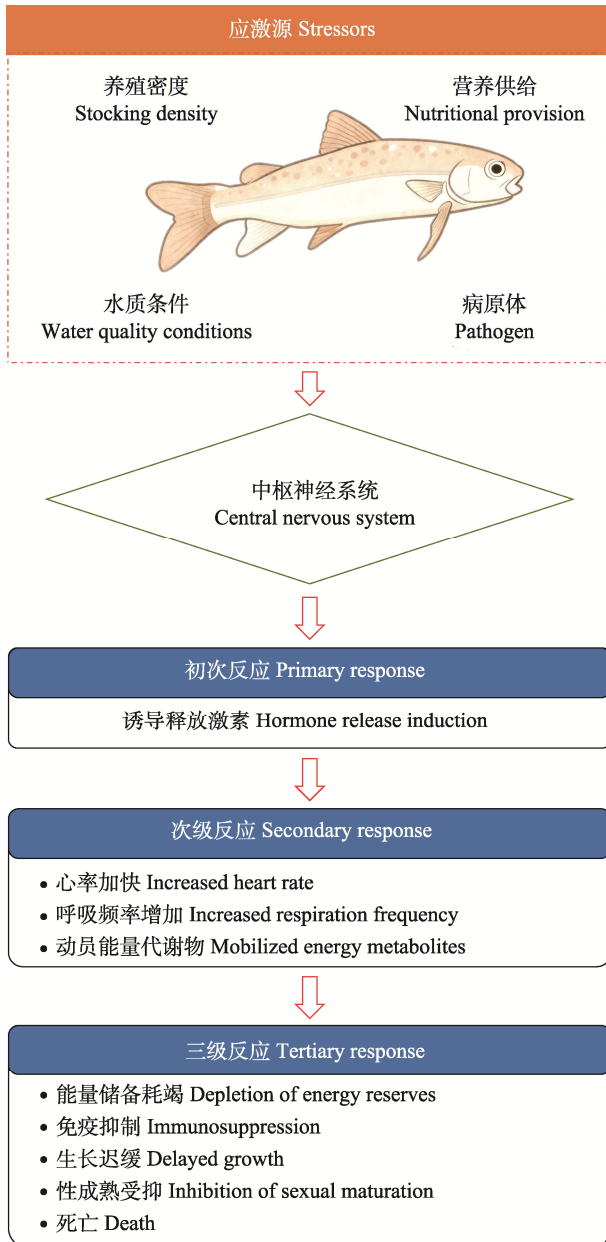


图1 鱼类生理应激反应
(引自 Jerez-Cepa *et al*, 2021)

Fig.1 Physiological stress response in fish
(Refer to Jerez-Cepa *et al*, 2021)

型参数包括红细胞(RBC)计数、血红蛋白(Hb)含量、白细胞(WBC)计数以及红细胞指数等(Fazio, 2019; Witeska *et al*, 2022)。此外,血清中的葡萄糖、总蛋白及脂质代谢产物等也可作为鱼类能量代谢和应激反应的指标(Andrade *et al*, 2015; Saha *et al*, 2023)。

3.3 新兴测试手段与综合评估方法

近年来,鱼类福利评估出现了多种新兴测试手段与综合评估方法。其中,基于情绪状态的评估方法受到广泛关注,主要包括认知偏差测试与偏侧性分析。

认知偏差测试通过动物对模糊刺激的反应(如判断偏差)来评估其情绪状态是积极还是消极,从而反映整体福利水平(Mendl *et al*, 2009; Lagisz *et al*, 2020)。该方法已被用于评估鱼类在不同环境、饲养和社交条件下的整体福利,并已在橘斑鲃丽鱼(Laubu *et al*, 2019)、东非慈鲷(*Neolamprologus pulche*) (Langérôme *et al*, 2025)、欧洲海鲈(Alvarado *et al*, 2023)等鱼类中成功应用,但其与动物偏好、急性与持续性福利体验之间的关系仍有待进一步明确(Paul *et al*, 2022)。偏侧性作为另一类潜在指标,是大脑半球在认知功能上的不对称处理产生的行为偏差(Berlinghieri *et al*, 2021)。由于不同半球分别处理积极与消极情绪,其行为表现可能反映动物当前的福利状态(Goursot *et al*, 2021),但也有学者表示,目前尚不确定偏侧性变化是否能够追踪鱼类福利状态变化(Browning, 2023)。在综合评估框架方面, Alvarado 等(2025)提出一种功能性评估框架,通过测量鱼类对环境的“偏好”和“为获取该环境所付出的努力(动机)”,验证其情感状态(判断偏差)以及生理、行为等健康指标是否一致指向福利改善,从而实现多层次的综合评估。此外,定性行为分析(Qualitative Behavioural Assessment, QBA)通过观察动物动态的肢体语言(体表、行为及其与环境互动)来判断福利状态,是简单、高效且非侵入性的综合评估方法(Stien *et al*, 2013; Vasdal *et al*, 2022),已应用于大西洋鲑对潜在应激的敏感性反应研究(Wiese *et al*, 2023)。在生产实践中,研究者已开发出多种结构化评估工具,如鲑鱼福利指数模型(SWIM) (Stien *et al*, 2013),适用于鲑鱼与鳟鱼的 FISHWELL 模型(Noble *et al*, 2018)以及 MyFishCheck 系统(Tschirren *et al*, 2021)等。这些评估模型或系统以鱼类福利为核心,通过一系列指标输出总体福利得分,并将输入与结果测量结合在一起,围绕生理适应与行为需求进行分组,并通过广泛的指标进行衡量(Browning, 2023)。类似地, Pedrazzani 等(2022)针对池塘养殖的草鱼,开发出基于环境、健康、营养和行为四个维度的福利量化体系,包含部分福利指数(PWI_i)与综合福利指数(GWI),为水产养殖中鱼类福利评估实践提供了重要参考案例。

4 总结与展望

尽管鱼类福利研究已取得系列重要进展,但其影响因素识别与评价方法构建方面仍面临多重挑战。一是环境变化带来新的福利风险。全球气候变化与人类活动持续改变鱼类生存环境,导致新型污染源与新发

表 2 鱼类福利评价的生理生化指标
Tab.2 Physiological and biochemical indicators in fish welfare evaluation

指标类别 Indicator categories	生理生化指标 Physiological and biochemical indicators	采样基质 Sampling matrixes	影响因素 Influence factors	物种 Species	参考文献 References
神经内分泌 Neuroendocrine	皮质醇	血浆	驱赶、抓捕、宰杀	虹鳟(<i>O. mykiss</i>) 大西洋鲑(<i>S. salar</i>)	Ding <i>et al.</i> , 2023; Saraiva <i>et al.</i> , 2024
	皮质醇	皮肤黏液、水	养殖密度、养殖模式	虹鳟(<i>O. mykiss</i>) 红罗非鱼(<i>Oreochromis</i> sp.) 尼罗罗非鱼(<i>O. niloticus</i>)	Mota <i>et al.</i> , 2017; Carbajal <i>et al.</i> , 2019; Alzate-Díaz <i>et al.</i> , 2025
	皮质醇	鳞片	养殖管理、养殖密度、驱赶	虹鳟(<i>O. mykiss</i>) 欧洲海鲈(<i>D. labrax</i>)	Carbajal <i>et al.</i> , 2019; Samaras <i>et al.</i> , 2021; Weirup <i>et al.</i> , 2021
	皮质醇	粪便	病原体感染、渗透压	大西洋鲑(<i>S. salar</i>)	Meling <i>et al.</i> , 2022; Ding <i>et al.</i> , 2023
神经毒性反应 Neurotoxic responses	AChE	大脑	重金属、杀虫剂	虹鳟(<i>O. Mykiss</i>) 低眼无齿巨鲶 (<i>Pangasianodon hypophthalmus</i>)	Kumar <i>et al.</i> , 2019; Uçar <i>et al.</i> , 2022
	PTG、PCG、AOPP	小肠	饥饿	闪光鲟(<i>Acipenser stellatus</i>)	Florescu <i>et al.</i> , 2021
氧化应激 Oxidative stress	T-AOC、CAT、SOD、GR、GPx、GST 等	肝脏	养殖密度、pH	塞内加尔鲷鱼(<i>S. senegalensis</i>) 黑鲷(<i>S. schlegelii</i>)	Andrade <i>et al.</i> , 2015; Li <i>et al.</i> , 2023
	MDA、TBARS	肝脏、血液	养殖密度、活体运输	斑点叉尾鲟(<i>I. punctatus</i>) 塞内加尔鲷鱼(<i>S. senegalensis</i>)	Andrade <i>et al.</i> , 2015; Refaey <i>et al.</i> , 2018
黏膜免疫 Mucosal immune	8-OHdG	肝脏、血液	抗生素、杀虫剂	虹鳟(<i>O. Mykiss</i>) 尼罗罗非鱼(<i>O. niloticus</i>)	Alak <i>et al.</i> , 2017; Farag <i>et al.</i> , 2021
	免疫球蛋白(IgM/IgT)、溶菌酶、补体因子与黏蛋白等	皮肤黏液、鳃、肠道、肝脏	实验操作、病原体感染	金头鲷(<i>S. aurata</i>) 草鱼(<i>C. idella</i>) 西伯利亚鲟(<i>A. baerii</i>)	Shen <i>et al.</i> , 2012; Fan <i>et al.</i> , 2015; Sanahuja <i>et al.</i> , 2023
血液学与血清生化指标 Hematology and serum biochemical indicators	RBC、PCV、Hb、MCV、MCH、MCHC、WBC、TC、HCT 等	血液	硝酸盐、杀虫剂	翠鳢(<i>C. punctata</i>) 草鱼(<i>C. idella</i>)	Farag <i>et al.</i> , 2021; Saha <i>et al.</i> , 2023
	葡萄糖、总蛋白、血清白蛋白、球蛋白、胆固醇、甘油三酯等	血液	养殖密度、pH	尼罗罗非鱼(<i>O. niloticus</i>) 翠鳢(<i>C. punctata</i>) 草鱼(<i>C. idella</i>) 塞内加尔鲷鱼(<i>S. senegalensis</i>)	Andrade <i>et al.</i> , 2015; Saha <i>et al.</i> , 2023

病原体不断涌现,使鱼类福利威胁日趋复杂。现有评估体系对这些新型风险识别的灵敏度与适应性仍有待系统验证。二是鱼类福利评价指标体系尚不完善。行为学指标在实际应用中存在界定与量化困难,“正常行为”的界定因物种、环境与应激强度差异而难以统一,用于福利评估的行为指标覆盖不全(如求偶、护幼等关键行为仅停留在描述讨论层面,且缺乏可操作的量化标准);生理生化指标虽能有效反映应激状态,但多依赖侵入性采样,易对鱼体造成二次伤害且难以实现连续动态监测。三是实验室研究与实际应用的脱节。尽管福利研究整体呈上升趋势,但实验室开发的精细指标与生产实际适用的简易指标之间存在明显脱节,导致综合性评估工具匮乏,可供生产实践直接应用的操作性指标严重不足。四是鱼类福利理念在生产实践中普及程度有限。尽管消费者与从业者对动物福利的认知逐步提升,但实际生产决策仍普遍以经济效益为核心导向,动物福利尚未成为经营管理的关键考量因素。

为应对上述挑战,未来鱼类福利研究建议重点关注以下方面:一是环境风险识别方面,需要系统研究新型污染物和病原体对鱼类的影响机制,建立相应的早期预警指标。积极研发新型监测手段,如利用生物传感器与生物记录仪实现血糖、代谢率等生理参数的连续无创监测,以及基于计算机视觉与声呐融合的自动化行为识别系统,这些技术可以有效降低人工观测的主观性与劳动成本,为规模化养殖条件下福利的客观评估提供支撑。二是评估体系建设方面,构建以“应激源-物种-指标-福利评价”为框架的多维评估体系,涵盖行为表现、生理生化反应、情绪状态、表观健康特征等多个层面。这一体系的建立需要基于大量的实证研究,通过不断的验证和完善,形成标准化的评估方案。同时,加强福利研究的应用转化,开发适用于不同生产场景的简易评估工具,推动实验室研究成果向实践应用转化。三是理念普及与法规建立方面,推动鱼类福利理念从理论认知转化为切实的管理实践,在技术、标准、法规与教育等领域形成合力。通过政府引导、科研支撑、产业实践与公众监督相结合,逐步完善覆盖鱼类在各种场景下的福利保障机制,通过健全法规、推广标准和提升公众素养等具体举措,将动物福利保护落实到渔业生产和生态保护,最终达成鱼类福利、生态保护与产业发展的协调统一。四是鱼类福利研究场景应受到特别关注(图2)。其中,(1)水产养殖与市场销售作为鱼类生产流通的关键环节,相关经营者需超越以经济效益为导向的决策模式。在从

种质选育到最终宰杀出售整个产业链中,应充分遵循鱼类自然行为与生理需求,建立适宜的养殖环境与科学管理体系;配套开发智能养殖系统,实现对环境参数和鱼类生理行为的实时监测与精准调控;推行符合动物福利原则的规范操作,在保障鱼类福利的前提下,实现水产品的优质安全生产与可持续发展。(2)在科学研究领域需加强从业人员的实验动物伦理教育,系统开展专业技术培训,内容涵盖暂养环境构建、卫生管理、规范操作及实验后处理等全流程。种质资源库的建立与长期维护,应充分考虑物种的自然习性需求,持续评估并改善保种群体的福利状况,在条件允许时适时进行种群更新。(3)增殖放流、保护区规划以及水利工程建设等人类干预活动可能对野生鱼类福利造成威胁。增殖放流需科学评估放流地的生态承载力和物种适应性,避免盲目放流导致生态冲击并防范遗传污染风险。保护区规划应明确保护鱼类的分布格局、生境需求及生态习性,制定物种特异性保护方案。水利工程建设应将生态影响作为首要评估指标,优化鱼道设计以适应鱼类游泳行为特性,保障其栖息需求,栖息地修复应遵循基于自然、适度干预的原则。(4)休闲垂钓、公园观赏与水族馆参观等公众活动应建立在科学管理的基础上。垂钓活动应推广使用无倒刺鱼钩等伤害较小的渔具,规范操作流程。动物园与水族馆应依据物种生态需求设计展示环境,实施环境丰容计划,制定符合鱼类自然节律的展示方案,引导游客文明观赏(如规范投喂、避免惊扰),构建动物福利优先、人与自然和谐共处的观赏模式。



图2 鱼类福利研究场景

Fig.2 Overview of fish welfare research scenarios

综上所述,未来鱼类福利研究应立足物种保护与伦理关怀,系统关注并改善各类场景下的鱼类福利问题。研究与实践需充分尊重鱼类生态习性,着力保障正常行为表达、维持健康生理状态并促进积极情绪体验,构建以政策法规为保障、科学研究为支撑、公众参与为基础的推进机制,最终实现产业实践与鱼类福利保护的协同发展。

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Research Progress on Influencing Factors and Evaluation Approaches for Fish Welfare

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Abstract In recent years, with the popularization and advancement of animal welfare concepts, the research scope has expanded from terrestrial to aquatic organisms. Related issues have garnered increasing attention from government agencies, animal protection organizations, researchers, and aquaculture practitioners. Habitat conditions, aquaculture practices, fishing methods, sales processes, and artificial stocking can potentially affect fish welfare. Based on an overview of the concepts and current progress in fish welfare research, this study summarizes the main factors affecting fish welfare. These encompass intra- and interspecific interactions, environmental conditions such as water quality, stocking density, and nutritional supply, as well as key production management measures including genetic breeding, live transport, grading, and slaughter. This study further reviews relevant evaluation indicators for fish welfare, including (1) behavioral metrics such as swimming activity, exploration, aggression, schooling, respiratory rate, feeding, stereotyped behaviors, and escape attempts; (2) physiological and biochemical parameters such as neuroendocrine regulation, oxidative stress, and immune and hematological responses; and (3) emerging and integrated assessment approaches, including methods based on cognitive bias tests and lateralization analysis, as well as other comprehensive evaluation methods and welfare assessment tools. However, the limitations of the current fish welfare research were highlighted and future work, grounded in species conservation and ethical considerations to systematically address fish welfare issues across different scenarios, was emphasized. Fully respecting the ecological habits of fish was proposed, focusing on safeguarding their natural behavioral expressions and maintaining their healthy physiological states. In addition, establishing a fish welfare advancement mechanism underpinned by policy and regulations, supported by scientific research, and aimed at public participation, to achieve coordinated development of fisheries production practices and fish welfare protection was emphasized. This study provides a theoretical basis for establishing a standardized fish welfare assessment framework and promoting welfare-oriented, healthy aquaculture practices.

Key words Fish welfare; Evaluation indicators; Stress; Aquacultural health

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