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·综述·

团头鲂全产业链健康养殖技术研究进展及展望

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摘要： 团头鲂是我国主要的淡水养殖鱼类之一，其具有食性广、养殖成本低、生长快、成活率高、易捕捞、易繁殖等特点，且具有味美、头小、含肉率高、体形好、规格适中等优点，深受消费者欢迎，在增加优质水产动物蛋白供应、提高全民营养健康水平、保障我国食物安全等方面做出了重要贡献。本文综述了团头鲂全产业链技术研究进展，包括新品种培育及育种技术、饲料营养需求调控及投喂技术、养殖应激与病害的生态防控技术、新型养殖模式、营养品质及加工技术等，提出了具有生产性能优、抗病抗逆性强和适于加工的团头鲂种质资源的挖掘，集约化健康养殖模式建立及精准营养供给、生态防控和高品质加工调理技术的研发等产业发展需求和研究方向，以期为团头鲂全产业链的绿色高质量可持续发展提供参考。

关键词: 团头鲂；全产业；育种技术；饲料营养；健康养殖；高品质加工
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1　团头鲂的来源与历史文化

自古以来，鲂是我国主要的淡水养殖品种，包括团头鲂 (*Megalobrama amblycephala*)、三角鲂 (*M. terminalis*)、广东鲂 (*M. hoffmanni*)、厚颌鲂 (*M. pellegrini*) 等多个种类，分布广泛，有着悠久的养殖历史。我国第一部辞书《尔雅·释鱼》记录，鲂“江东呼鳊鱼之美者”。鲂中最常见的是团头鲂，也被称为武昌鱼，其中的“武昌”是指三国时期吴王朝的发源地古武昌，也就是今天的鄂州。“武昌鱼”这一名字一直延续了一千多年，直到 1955 年，我国著名鱼类学家易伯鲁详细鉴定认为，武昌县牛山湖 (梁子湖湖汊) 的团头鲂，头更小，体更长更扁，产区也较集中，肉质细嫩、鲜美、营养成分又优于其他种类，并将其命名为团头鲂，分类学上隶属于鲤形目 (Cypriniformes) 鲤科 (Cyprinidae) 鲂属 (*Megalobrama*)。易伯鲁则被尊为“武昌鱼之父”。

在漫长历史岁月中，武昌鱼文化已经演化为渔文化发展的一个分支。武昌鱼先后被孟浩然、杜甫、苏轼、王安石、范成大、岑参、陆游等 120 多位文人吟诵，留下吟咏武昌鱼的诗词逾百首。1956 年，毛泽东所做的《水调歌头·游泳》中“才饮长沙水，又食武昌鱼”令武昌鱼蜚声中外。据中国渔业统计年鉴报道，2022 年，我国鳊鲂类

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总养殖产量为 76.7 万 t (团头鲂占 90% 以上)，全产业链年产值约 450 亿元，在我国淡水养殖鱼类产量中排名第八位，具有重要的社会和经济价值。

2 团头鲂新品种培育及育种技术

水产种业是渔业科技的芯片，是保障水产品粮食安全、食品安全和生态安全的根本，现代水产种业是水产养殖业绿色高质量发展的重要物质基础和核心竞争力。截至 2023 年，国家水产良种审定委员会审定通过了性状稳定遗传的 3 个团头鲂选育新品种，其中，团头鲂“浦江 1 号”具有体型好、个体大、生长快、适应性广等特性，团头鲂“浦江 2 号”生长快、耐低氧能力提升，团头鲂“华海 1 号”具有生长快、成活率高的特点。此外，还审定通过了鲌鲂“先锋 2 号”、鳊鲴杂交鱼、芦台鲂鲌、太湖鲂鲌、杂交鲂鲌“皖江 1 号”等 5 个杂交新品种。这些新品种在全国得到了大面积的推广应用，极大地提高了团头鲂的养殖经济效益。

21 世纪以后，由于人工驯养群体退化、过度捕捞和水域污染等问题，团头鲂天然种质资源也面临严重的威胁，许多研究者开始利用随机扩增多态性 DNA (random amplification polymorphic DNA，RAPD)、线粒体 DNA (mtDNA)、微卫星 (microsatellite) 等分子标记来调查和评估团头鲂野生群体和养殖群体的遗传多样性现状[1-4]。基于多态性微卫星标记，以选育基础群体的父母本的基因型为基础，构建了团头鲂亲子鉴定技术平台，用于家系鉴定[5]。随着高通量测序技术的快速发展，团头鲂全基因组成功构建[6]，同时结合多组学技术，筛选了生长、抗病、耐低氧、肌间刺、性腺发育等选育性状相关 SSR 和 SNPs 标记[7-10]，并开展相关经济性状的遗传参数评估[11-14]，选育目标逐渐发展，并聚焦至生长快、抗病力强、耐低氧和肌间刺少等经济性状。华中农业大学高泽霞教授团队在肌间刺研究方面，筛选到调控肌间刺发生发育的关键基因 *runx2b*，通过 CRISPR/Cas9 编辑技术，培育出完全无肌间刺的团头鲂新种质[15]，并将该项技术成功应用在鲫 (*Carassius auratus*)、草鱼 (*Ctenopharyngodon idella*) 等品种的无肌间刺选育工作中。在耐低氧方面，上海海洋大学邹曙明教授团队通过挖掘获得低氧诱导因子抑制因子 1 (factor inhibiting HIF-1, fih1) 等关键调控基因，评价了杂交鲂 [*M. amblycephala*(♀)×*Culter alburnus*(♂)] F_3 杂交种耐缺氧性能[16-18]。因此，下一步可以通过制定合适的选择性育种策略，借助数量遗传学和基因编辑、基因组学等先进的现代育种技术，聚焦饲料转化率高、无肌间刺、性别控制、抗病力强和环境适应性强等育种性状的研究和选育将是团头鲂新种质创制和育种的发展方向，不仅可以大大加快团头鲂良种选育的进程，实现更快、更有效地进行鱼类良种选育和品种改良，还有助于满足不断增长的水产食品需求，在水产养殖的生产效率、可持续性和抗病能力方面起到关键作用。

3 团头鲂精准营养调控及投喂技术

3.1 团头鲂的饲料营养需求

饲料中蛋白质、氨基酸、必需脂肪酸、维生素和微量元素等营养素的供应不足常常会导致鱼类营养不良、抵抗力降低，且高密度集约化养殖模式的发展带来养殖水环境不稳定、病原微生物易滋生等问题，极易引起团头鲂养殖中病害频发、甚至死亡的情况，严重阻碍了其养殖产业的持续健康发展。2010 年以来，国内研究团队系统构建了不同规格团头鲂对饲料蛋白质、脂肪、碳水化合物、氨基酸、维生素和矿物质等营养素需求量数据库，在此基础上于 2022 年正式发布了《团头鲂配合饲料》行业标准。不同研究者得到的团头鲂对饲料蛋白质的需要量受水温、鱼体大小和原料品质等因素的影响存在差异。水温为 20 °C 时，团头鲂鱼种对蛋白质的适宜需求量为 27%~30%；水温为 25~30 °C 时，则提高至 25.6%~41.4%[19]。从生长性能来看，团头鲂幼鱼 (体重<20 g) 饲料蛋白质的适宜需求量为 30%~32%[20-21]；1 龄团头鲂 (21.4~50.0 g)对饲料蛋白质需求量为 21.05%~30.83% [22-23]。鱼类对蛋白质的需求实际上是对氨基酸的需求，尤其是对必需氨基酸的需求。氨基酸营养研究报道，在团头鲂成鱼中 (体重>50 g)，异亮氨酸的需求量为 1.46%~1.47%、亮氨酸的需求量为 2.02%~2.17%、组氨酸的需求量为 0.60%~0.62%、精氨酸的需求量为 2.04%~2.08%[24]、蛋氨酸的需求量为 0.74%~0.76%[25]。在团头鲂幼鱼中 (体重<50 g)，蛋氨酸、赖氨酸、精氨酸、异亮氨酸、亮氨酸和缬氨酸的需求量分别为 0.85%[26]、2.36%[27]、2.46%[28]、1.38%[29]、1.44%[30] 和 1.32%[31]。对于饲料中的脂肪含量，12~15 g 的团头鲂幼鱼对

饲料中脂肪的需求量为 2%~5%[32]，而 1 龄团头鲂饲料中脂肪适宜含量为 6%[23]。团头鲂属草食性鱼类，对饲料糖类利用和代谢能力也相对较强，其饲料中适宜的糖水平为 31%[33]，脂肪和糖类均可为鱼类提供能量，起到节约部分蛋白质的作用。糖脂比为 2.45~5.64 时，团头鲂幼鱼 (6.6 g) 获得最佳生长，经过回归拟合确定团头鲂幼鱼饲料最适糖脂比为 3.58[34]。维生素和矿物质为微量元素，其在饲料中保持适宜的含量有利于团头鲂生长、缓解炎症反应等[35-36]。Hao 等[37] 发现 0.96 mg/kg 硒添加量为最佳添加浓度，添加适当酵母硒可以提高团头鲂肉质[38]。同样，添加 366.67 mg/kg 的镁[39] 也能提高肌肉纤维密度。团头鲂幼鱼饲料中添加 150 mg/kg 维生素 C 可以提高鱼体抗氧化能力[40]。饲料中添加 294 mg/kg 肌醇、5.43 IU/g 维生素 D_3 可显著提高团头鲂特定生长率[41-42]，当饲料中维生素 E 和维生素 B_3 的含量分别为 138.5 和 31.25 mg/kg 时，团头鲂幼鱼具有最佳的增重率[43-44]。总的来说，随着近年全球气候的不断变化和水产养殖业不断发展，针对不同环境条件和养殖方式的营养需求体系的研究也在不断演进，此外，不同团头鲂养殖品种和品系在饲料营养需求方面的遗传差异也是学者关注的方向。

3.2　团头鲂新饲料原料的开发

我国水产饲料产量从 1991 年的约 75 万 t 已经发展到了 2022 年的约 2 525 万 t。然而，随着水产配合饲料快速发展，饲料资源，尤其是优质蛋白原料资源短缺的问题已日益凸显。据不完全统计，我国年需蛋白质饲料原料 8 000 万 t 以上，每年缺口 4 000 万 t 以上，而且优质蛋白饲料资源有限。因此，开发新型非粮蛋白源，降低水产饲料生产对鱼粉、豆粕等资源紧缺性饲料原料的依赖性，是当前水产饲料产业发展的重要方向。围绕非常规蛋白原料消化利用率的研究显示，团头鲂对玉米蛋白粉、玉米及碎米等干物质的表观消化率均达到 91% 以上，对血粉、蚕蛹粉及大麦中干物质的表观消化率为 73.00%~79.33%[45]。新型农产品加工副产物等原料的利用，如发酵豆粕[46]、大米蛋白[47]、棉籽粉[48]等替代饲料中适量的鱼粉，能够对团头鲂生长性能、肠道功能及氨基酸代谢等具有积极影响。为应对全球资源的紧缺，开发植物蛋白、昆虫蛋白和单细胞蛋白等可替代传统蛋白质来源的原料，建立多元化的饲料配方体系是降低水产饲料对大宗原料的依赖度、减少饲料生产对生态系统的负面影响和降低生产成本的重要途径。此外，通过理化手段改良饲料原料的性状、利用定向微生物工程技术降解植物原料中的抗营养因子，改进饲料原料的品质、可持续性和消化利用效率也将是饲料端提质增效的研究热点。

3.3　团头鲂的科学投喂技术

随着团头鲂密集型养殖产业的不断发展，不科学的投喂方式不仅影响生产性能，而且造成饲料浪费和氮磷的过度排放，导致养殖效益下降和环境的恶化。徐超等[49] 的研究表明，团头鲂幼鱼的每日最适投喂量为体重的 4.57 %。投喂频率过低或过高都可引起团头鲂幼鱼氧化应激，从而导致其免疫力下降，降低其对嗜水气单胞菌感染的抵抗力[50]。在循环流水控温养殖方式下，投喂频率为每天 5 次时团头鲂幼鱼可获得快速、健康的生长，且可保持鱼体肌肉品质，因此建议团头鲂幼鱼养殖的投喂频率为每天 5 次[51]。饲料精准投喂是一种现代养殖管理方法，旨在提高养殖效益、减少资源浪费和环境污染。随着大数据技术和人工智能在水产养殖中的深入应用，建立团头鲂不同生长阶段的营养需求模型和精准配方技术体系，利用传感技术收集水产养殖动物的分布、生长状态和摄食行为等监测数据，优化调整投喂饲料量和投喂频率，研发智慧化投喂设备和应用技术是团头鲂高质量养殖的必然发展趋势。

4　团头鲂养殖应激与病害的生态防控技术

4.1　团头鲂养殖应激的绿色防控技术

鱼类病害发生主要与病原体、水体环境和宿主有关，是三者之间共同作用的结果[52]。团头鲂对各种环境因素刺激 (例如氨氮、亚硝酸盐氮、缺氧、pH 和养殖密度等) 的应激反应较为强烈，严重影响生长效率、饵料系数和免疫力，增加疾病感染风险[53]。水体氨氮和亚硝酸盐氮含量偏高是细菌性败血症暴发的诱因之一，水中未离解的氨对鱼类有很强的毒性作用，即使在低浓度下也会通过 GH/IGF 轴抑制团头鲂的生长，损伤其组织结构，降低肌肉品质[54-55]。氨氮胁迫下，团头鲂不同器官之间的病理损伤程度不同，其中肝、鳃和肾的损伤程度相对较为严重[56]。急性亚硝酸盐暴露时，代谢废物随着暴露时间的延长发生积累，

不仅导致组织损伤，还降低鱼体多不饱和脂肪酸的含量，改变团头鲂肌肉的物性特征[57-58]。高温应激后，团头鲂肝脏超微结构受损，免疫系统的效能下降，嗜水气单胞菌 (*Aeromonas hydrophila*) 感染后死亡率增加[59]。高密度 (>60 尾/m^3) 养殖条件下团头鲂肝脏出现损伤，抗氧化能力显著下降，同时肠道消化酶活性降低，且伴随着肠道优势菌群的变化和炎症反应的发生[60]。低氧对团头鲂幼鱼有负面影响，能够导致心肌肌纤维排列紊乱、肿胀甚至断裂，鳃、肝脏和肾脏严重的氧化损伤，主要表现为鳃小片充血甚至融合、肝细胞中脂肪变性、肾小球萎缩或坏死等[60-61]。研究发现，在饲料中添加黄连素[62]、阿魏酸[63]、益生菌[64]、抗菌肽[65]等免疫增强剂[66]，可以通过免疫刺激改善团头鲂生长性能，增强机体抗氧化能力，提高鱼体肌肉风味物质含量，提升水产品食用品质。肌醇[67]、叶酸[68]、维生素 E[69]、铬[70]等营养性饲料添加剂有助于缓解高温对团头鲂血液生理生化的影响，即使在高温胁迫下也显示出其保肝作用 (提高抗氧化能力和 *hsp*70、*hsp*90 的表达)，促进鱼体生长。基础饲料中添加酵母硒、茶多酚及其配伍均可提高肝脏抗氧化性能并上调 *hsp*70 表达，缓解亚硝酸盐对团头鲂造成的氧化应激[71]。果寡糖[72-73]、微囊丁酸钠[74]、大黄素[75-76]、大黄蒽酮提取物[77]等功能性饲料添加剂可提高团头鲂的免疫能力，保护细胞结构，改善肝脏功能，增强抵抗氨氮应激、高密度养殖应激等能力。

4.2　团头鲂养殖病害的生态防控技术

从病原来看，嗜水气单胞菌是团头鲂细菌性败血症的主要病原，是条件致病菌[78]。研究人员通过调查团头鲂养殖池塘气单胞菌的核糖型、毒力基因的多样性以及毒力基因谱的多样性，发现溶血素为最常见的毒力基因[79-80]，并建立团头鲂嗜水气单胞菌出血病暴发前后水体及鱼体血液中细菌的动态变化模型。随着集约化养殖模式的发展和养殖规模的扩大，不可避免地会引起养殖环境的变化和鱼体抗病、抗逆等生理状态的应激反应。近年来，绿色生态养殖观念已被广泛接受，坚持以防为主的综合生态防控技术成为未来的发展方向，有助于将病害损失和安全风险降到最低[81]。研究发现，棉籽粕蛋白水解物[82]、发酵银杏叶[83]、三丁酸甘油酯[65]、维生素 A[84]、维生素 C[85-86]、维生素 D_3[87]、乳酸芽孢杆菌[88]、粪链球菌[89]、酵母硒和茶多酚[90]、蛋黄免疫球蛋白[91]、黄连素[92]、大黄素[93]、果寡糖[94]、低聚木糖[95]、甘露聚糖[96]、壳寡糖[97]等功能性饲料添加剂能提高团头鲂抗嗜水气单胞菌感染的能力。另外，生产活动中养殖动物的福利也将是一个新的关注方向，例如，为养殖对象提供一个符合其生物习性、适宜其生长和生理状态的养殖环境，并提供充足的饵料供给、病害防治措施和精准管控规程保障的条件和环境。因此，通过研究团头鲂主要病原体的生态学和流行病学，研发高效绿色的生态防控技术和产品，这将是今后保障养殖动物福利、缓解环境应激损失的重要手段之一。

5　团头鲂养殖新模式新技术

近年来，全国各地相继出台了水产养殖尾水排放标准，并要求严格执行。在团头鲂的池塘精养模式中，基于对水生植物净化效率的研究和养殖鱼类产排污系数的调查统计，在生态养殖容量研究中发现养殖池塘与净化池塘的适宜面积比约为 10∶1[98]。多级净化池塘中，基于比较研究水葫芦、水花生、水上农业、水生植物化感、固定化微生物等对水质改良和净化的效果，形成一整套针对池塘三级净化循环水大宗淡水鱼类养殖水质净化技术[99]，水体氨氮的平均去除率达 60.49%、亚硝酸盐氮为 86.51%、总氮为 74%、总磷为 68.5%、叶绿素 (藻类) 为 73.67%，可实现养殖水体循环利用，从而达到养殖废水零排放的目的。国内专家利用“流水+水质净化+捕捞曝气模块”三大核心技术构建了两种养殖密度 (10 和 5 kg/m^3) 的团头鲂池塘内水池养殖 (in-pond tank culture system, IPTCS) 系统，有效养殖面积占池塘面积的 10%，水质净化效果显著提升：与原水相比，固液分离塔和垂直流人工湿地处理对总氨氮、亚硝酸盐氮、可溶性活性磷、总氮和总磷的去除率分别达到 86.82%、85.45%、16.36%、64.19% 和 56.76%，这一研究结果表明 IPTCS 系统的团头鲂高密度养殖模式获得了最佳投资回报率[100]。同样，在跑道式循环水养殖模式中，通过饲料配方和功能性添加剂的应用可以提高团头鲂池塘高密度工业化循环水养殖的适应性和抗应激性，改善肌肉品质和营养成分，提高团头鲂高密度养殖模式的经济效益[101-102]。此外，生物絮团技术同样可应用于团头鲂养殖，其适宜的碳氮比在不低于 16 的条件下形成的生物絮团能有效提高团头鲂生长、消

化和免疫相关酶活性[103-104]。通过集成以上技术，建立的团头鲂循环水生态健康养殖模式实现了池塘养殖水体循环使用，从而达到养殖废水零排放的目的[105]。在生态环境保护和绿色健康发展的双重需求下，对养殖尾水处置后达标排放的要求日趋严格，全国各地陆续出台了《池塘养殖尾水排放强制性标准》。随着陆基圈养模式、跑道式循环水养殖模式、池塘循环水养殖模式和鱼菜共生等健康养殖模式的涌现，其中关键的养殖尾水净化、资源化利用和节能减排等配套技术的研发也亟需跟进，构建生态化、集约化、智能化等全程可控养殖系统，推动团头鲂传统池塘养殖转型升级和绿色发展。

6 团头鲂营养品质及加工技术

团头鲂的烹饪技艺发展始萌于春秋战国时期，北魏贾思勰的《齐民要术》、清代著名食书《随园食单》《调鼎集》均收集了团头鲂烹饪技法，由于其味道鲜美，成为了一道具有悠久历史的名菜。1965 年，团头鲂被正式定名为湖北省地方风味菜肴，成为鄂菜的当家美食，其制作技艺也成为湖北省非物质文化遗产。

水产品传统的品质评价指标包括感官、理化指标、微生物指标等。近年来，随着蛋白质组学分析技术、电子鼻、电子舌等新型检测方法的日益广泛应用，团头鲂的营养评估和初深加工技术的研究获得快速发展。团头鲂的营养和品质受养殖模式、捕获季节、鱼体规格和加工方式等多种因素影响[106-107]。李温蓉等[108] 比较了池塘养殖和大湖养殖对团头鲂鱼肉品质的影响，发现大湖养殖团头鲂的肌肉质地、营养品质均优于池塘养殖，有利于加工后营养及风味品质提升。郭晓东等[109] 发现加工前采用循环水净化装置对团头鲂净化处理 8 d，可显著改善鱼肉的食用品质。杜柳等[110] 发现，相比自然解冻、超声解冻和低温解冻，静水解冻后干制团头鲂的品质及风味更优。

团头鲂因其鱼价较高、采肉率较低、鱼糜胶凝能力较弱，不适合作为鱼糜及其制品生产原料，但鱼头、内脏等占比较小，脏体指数较小，鱼肉含水量较低，更适合加工成调理制品、干腌制品和休闲食品[111]。随着水产食品加工技术的不断发展，团头鲂主要的加工技术有干制加工、熟制加工等。干制加工是我国水产食品的传统加工方法，温度对团头鲂肉质影响很大。有研究发现，联合干燥 (冷风干燥 12 h 后转为热风干燥 10 h) 后团头鲂脂质氧化程度低、弹性好，挥发性风味物质含量多、种类丰富，优于热泵干燥、热风干燥和冷风干燥[112]。通过比较传统日晒和阴干两种干制方式下腌制团头鲂风味差异，发现传统日晒干制的团头鲂整体气味更加丰富[113]。熟制过程中，料汁中的小分子风味物质在高渗透压的作用下转移到鱼体内，使鱼体的蛋白质发生不同程度的分解，形成风味小分子肽。熊舟翼等[114] 发现，增加火候可使团头鲂色泽更加鲜明，增加浸泡保温时间可促进料汁渗透，增加总熟制时间可提升团头鲂氨基酸态氮和蒸煮得率。目前，随着加工技术的不断改进，人们将享用到营养品质更优、口感风味更佳的水产品。另外，随着水产品主要消费群体年龄结构和消费习惯的变化，预制加工和风味调理类水产品日益受到市场的欢迎，但仍缺乏统一的营养品质评价标准。因此，团头鲂加工调理、副产品资源开发利用、营养风味等比较研究仍需要不断完善，以满足消费者对团头鲂的需求。

7 展望

随着国民对优质水产品需求的不断上涨，水产养殖为解决我国城乡居民吃鱼难、增加优质动物蛋白供应、提高全民营养健康水平、保障我国食物安全等方面做出了重要贡献。随着国家水产养殖保护工作的不断深入以及未来环保政策的持续收紧，未来我国水产养殖面积将越来越紧缺。因此，具有生产性能优、抗病抗逆性强和适于加工的团头鲂种质资源的挖掘、集约化健康养殖模式的建立及精准营养供给、病害生态防控和加工调理技术的研发，将是形成团头鲂全产业链闭环、提高团头鲂产业发展潜能、实现产业可持续发展的重要方向。

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Progress and prospects of healthy aquaculture technology for the whole industrial chain of *Megalobrama amblycephala*

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Abstract: *Megalobrama amblycephala* is one of the main freshwater aquaculture species in China, with the advantages of wide feed habits, low culture cost, rapid growth performance, high survival rate, and easy to farm and harvest. *M. amblycephala* has the characteristics of delicious flavour, high rate of edible meat, good body shape, etc., which are popular among consumers and have made an important contribution to increasing high-quality aquatic animal protein supply, improving the nutritional health of the nation, and guaranteeing the food security in China. This review summarizes the progress of the current researches and developments on whole industrial technology of *M. amblycephala*, including innovations on breeding technology, nutritional regulation and feeding technology, ecological prevention technology from aquaculture stress and disease, health farming technology, nutritional quality and processing technologies, etc.. Based on the progresses, the industrial development requirements and research directions on germplasm resources excavation with production performance, excellent disease and stress resistance, and suitable for processing, the establishment of intensive healthy breeding mode and precise nutritional supply, ecological prevention technology innovation, high-quality processing and conditioning technology are proposed. This review is expected to provide references for the green, high-quality and sustainable development of the whole industrial chain of *M. amblycephala.*

Key words: *Megalobrama amblycephala*; entire industry; breeding technology; feed nutrition; healthy aquaculture; high-quality processing

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