第43卷 第2期 华 中 农 业 大 学 学 报 Vol.43 No.2
2024年 3月 Journal of Huazhong Agricultural University Mar. 2024,164~174

杨航,袁泉,吕巍巍,等.黑水虻幼虫的营养特性及其在水产饲料中的应用进展[J].华中农业大学学报,2024,43(2):164-174.
DOI:10.13300/j.cnki.hnlkxb.2024.02.019

黑水虻幼虫的营养特性及其在水产饲料中的应用进展

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摘要 黑水虻为一种腐食性昆虫,其幼虫具有食性广、繁殖力强以及营养物质丰富且均衡等特点,被认为是极具潜力的新型饲料蛋白质源,在水产动物生产中具有广阔的应用前景。本文概述了黑水虻幼虫的主要营养成分和生物活性成分,及其在草食性、杂食性、肉食性、甲壳动物和两栖爬行动物等不同水产养殖品种饲料中的应用研究进展,总结了不同水产动物饲料中黑水虻幼虫的最适用量,探讨了黑水虻幼虫作为水产饲料中可持续蛋白源的可行性及在实际应用过程中存在的问题及挑战,以期为黑水虻的开发利用及其在水产动物中的机制性研究提供依据和参考。

关键词 黑水虻; 营养学特性; 水产动物; 新型蛋白源; 水产饲料

中图分类号 S963; S816.48 **文献标识码** A **文章编号** 1000-2421(2024)02-0164-11

水产养殖为人类提供了重要的食物来源。随着我国水产养殖业的快速发展,水产饲料的市场需求量逐步提升。科学合理地配制水产饲料,对于提高养殖效益、保障养殖动物健康、保护环境等方面都具有重要意义。从营养学角度来看,鱼粉已被公认为是水产饲料中的最佳蛋白质来源,尤其是肉食性水产动物需要大量的鱼粉。然而,随着过度捕捞、人为活动以及极端天气等原因,全球范围内提供鱼粉的主要鱼类产量逐年降低,导致鱼粉短缺,价格上涨,因此水产养殖业的可持续发展亟需寻求可替代鱼粉的优质蛋白源。

昆虫作为一种新型蛋白源备受关注。目前全球已报道约有100万种昆虫。常用作饲料原料的昆虫主要有黑水虻、黄粉虫、大麦虫、蚕蛹、蝇蛆和蝗虫等,其粗蛋白含量与畜禽和水生动物相当,多数在21%~65%,且具有氨基酸较平衡、维生素和矿物质丰富以及含有多种生物活性成分等优点[1]。研究表明,鱼虾养殖中昆虫粉可以部分或完全取代饲料中的鱼粉,对水生动物生长、饲料利用、肠道健康、免疫能力以及肌肉品质无负面作用,某些昆虫蛋白还可产生积极影响[2]。其中,黑水虻被认为是最有希望替代水产饲料中鱼粉的蛋白源之一。

黑水虻(*Hermetia illucens* L.)属双翅目水虻科扁角水虻属,为一种完全变态昆虫。整个生命周期分别经历卵、幼虫、预蛹、蛹和成虫期,约35 d,发育周期根据温度和湿度有所变化[3]。饲用较广的为黑水虻幼虫粉,因脂肪含量较高,根据配方需求又分为全脂和脱脂黑水虻幼虫粉。此外,还有预蛹粉、干虫、鲜虫、酶解/发酵虫浆(膏)、酶解虫肽和虫油等多种加工产品。黑水虻作为水产饲料中鱼粉、豆粕等常规蛋白源的替代品,除了高营养价值外,还具有:(1)不携带细菌、安全可控;(2)生物量大,转化和产出效率高,且产出物基本实现了完全资源化;(3)幼虫个体大,容易收集并适宜较长时间保存;(4)可以解决环境卫生问题,有助于可持续发展等优点。基于黑水虻优秀的生物学特性和高营养价值,本文总结了黑水虻幼虫的营养学特征以及其在不同水产养殖品种配合饲料中的应用研究进展,以期为黑水虻的开发利用及在水产动物中的机制研究提供理论依据和参考。

1 黑水虻的营养学特性

黑水虻幼虫粉及水产饲料中主要蛋白源的营养成分对比见表1~4。黑水虻的营养组成与培养基料

收稿日期: 2023-08-29
基金项目:上海市2023年度“科技创新行动计划”农业科技领域(23N61900500);国家特色淡水鱼产业技术体系(CARS-46)
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成分间存在显著相关性，故不同培养基上养殖的黑水虻营养成分差异较大[4]。用于黑水虻幼虫培养的有机物包括水果废弃物、蔬菜废弃物、混合餐厨垃圾以及鸡粪、猪粪、牛粪和混合动物粪等不同类型。此外，幼虫风干后水分、幼虫日龄、测定指标方法以及加工方式也是造成差异的原因之一。目前，饲用黑水虻质量标准只有企业标准和团体标准，暂无国家和行业标准。其中以 T/GZZX 4—2018《饲料用干黑水虻虫》中特级产品为例，基础营养成分要求为：粗蛋白≥40%、粗脂肪≥32%、水分≤12%、灰分≤20%、钙 3.0%～5.0%、总磷 0.5%～1.5%。而在氨基酸和脂肪酸组成以及矿物质含量方面暂无统一标准。整体而言，黑水虻幼虫粉与常用饲料蛋白源在营养成分上各有优劣。但黑水虻的营养价值为可控因素，通过改善培养基的营养组成可以强化黑水虻某些营养成分的含量。目前，黑水虻及其虫油常用于部分替代饲料中鱼粉、豆粕和鱼油、豆油等主要蛋白源和脂肪源，或是作为单独原料搭配使用。

表 1　黑水虻幼虫及水产饲料中主要蛋白源的常规营养成分

Table 1　Proximate composition contents of black soldier fly larvae and major protein sources in aquafeeds　%

指标 Indicators	黑水虻幼虫[4] Black soldier fly larvae	鱼粉(CP 67%)[5-6] Fish meal	肉骨粉[5-6] Meat and bone meal	豆粕[5-6] Soybean meal
粗蛋白质 Crude protein	23.80～62.70	67.10	50.00	47.90
粗脂肪 Crude fat	4.70～38.60	7.50	8.50	1.50
粗灰分 Crude ash	6.40～19.70	12.30	31.70	4.90
钙 Ca	0.20～4.96	3.80	9.20	0.34
总磷 P	0.39～3.50	2.60	4.70	0.65

表 2　黑水虻幼虫及水产饲料中主要蛋白源的必需氨基酸组成

Table 2　Essential amino acid contents of black soldier fly larvae and major protein sources in aquafeeds　%

氨基酸 Amino acid	黑水虻幼虫[4] Black soldier fly larvae	鱼粉(CP 67%)[5-6] Fish meal	肉骨粉[5-6] Meat and bone meal	豆粕[5-6] Soybean meal
赖氨酸 Lys	1.22～6.45	4.97	2.60	2.99
蛋氨酸 Met	0.54～6.10	1.86	0.67	0.68
苏氨酸 Thr	1.42～3.92	2.74	1.63	1.85
精氨酸 Arg	1.10～5.22	3.93	3.35	3.43
缬氨酸 Val	1.87～7.20	3.11	2.25	2.26
异亮氨酸 Ile	1.12～5.08	2.61	1.70	2.10
组氨酸 His	1.19～1.94	2.01	0.96	1.22
亮氨酸 Leu	2.73～5.48	4.94	3.20	3.57
苯丙氨酸 Phe	1.65～2.85	2.61	1.70	2.33
色氨酸 Try	0.68～0.94	0.77	0.26	0.65

表 3　黑水虻幼虫及水产饲料中主要蛋白源的部分脂肪酸组成

Table 3　Partial fatty acid contents of black soldier fly larvae and major protein sources in aquafeeds　%

脂肪酸 Fatty acid	黑水虻幼虫[4] Black soldier fly larvae	鱼粉(CP 67%)[5-6] Fish meal	肉骨粉[5-6] Meat and bone meal	豆粕[5-6] Soybean meal
月桂酸 C12:0 Cinuric acid C12:0	7.50～49.34	–	0.20	–
豆蔻酸 C14:0 Cardamic acid C14:0	1.90～10.20	6.00	2.70	0.10
棕榈酸 C16:0 Palmitic acid C16:0	5.30～19.20	17.80	27.50	10.50
棕榈油酸 C16:1 Palmitic acid C16:1	0.80～5.82	7.20	3.70	0.20
硬脂酸 C18:0 Stearic acid C18:0	2.78～25.10	3.60	19.20	3.80
油酸 C18:1 Oleic acid C18:1	7.30～26.60	12.30	40.70	21.70
亚油酸 C18:2 Linoleic acid C18:2	2.70～57.25	2.10	3.60	53.10
亚麻酸 C18:3 Linolenic acid C18:3	0.20～24.30	1.90	0.90	7.40

表4　黑水虻幼虫及水产饲料中主要蛋白源的部分矿物质含量

Table 4　Partial minerals contents of of black soldier fly larvae and major protein sources in aquafeeds

矿物质 Minerals	黑水虻幼虫[4] Black soldier fly larvae	鱼粉(CP 67%)[5-6] Fish meal	肉骨粉[5-6] Meat and bone meal	豆粕[5-6] Soybean meal
钠/% Na	0.24～2.25	1.04	0.73	0.03
镁/% Mg	0.26～0.40	0.23	1.13	0.28
钾/% K	0.49～1.58	0.74	1.40	1.72
铁/(mg/kg) Fe	80～20 000	337	500	185
铜/(mg/kg) Cu	6.0～4 000	8.4	1.5	24
锰/(mg/kg) Mn	246～2 600	11	12.3	28
锌/(mg/kg) Zn	108～3 000	102	90	46.4

2　主要生物活性成分

2.1　甲壳素

甲壳素(chitin),又称几丁质或壳多糖,为N-乙酰葡糖胺通过β连接聚合而成的结构同多糖,广泛存在于昆虫的甲壳以及甲壳类动物的外壳中,其理化性质和产量因昆虫种类而不同[7]。黑水虻成虫的骨骼和鞘翅、幼虫的表皮以及蛹壳都是由几丁质构成,其不同阶段(幼虫、预蛹、蛹和成虫)均可以提取甲壳素,但不同阶段的甲壳素差异较大。Wang等[8]研究表明,上述4个阶段的甲壳素含量分别为3.6%、3.1%、14.1%和2.9%,故从蛹期提取甲壳素的效率较高。甲壳素不易被降解,但可被水产动物肠道微生物发酵,从而增加肠道有益菌数量,恢复肠道微生物群落的组成平衡,进而调节肠道消化能力、脂代谢以及机体免疫力等作用[9]。然而,Karlsen等[10]在鱼类研究中表明,过量甲壳素会降低生长以及蛋白质和脂质等营养物质消化性能。这也是饲料中黑水虻幼虫粉添加量过多,造成水产动物生长和饲料利用降低的主要原因之一[11-12]。

2.2　抗菌肽

抗菌肽(antimicrobial peptides,AMPs)是昆虫在受到感染或伤害时,产生的一类具有抗菌活性的碱性多肽物质,是昆虫宿主天然免疫系统的主要构成成分。这类活性多肽因具有良好的广谱抗菌、热稳定性以及安全性等生物活性特点,尤其是对某些耐药性病原菌也有一定的杀灭作用,故具有较大的“替抗”潜力[13]。

黑水虻作为自然界食物链中的分解者,长期生活于含有较多有害细菌和病毒的有机废弃物中,逐渐形成了较强的免疫机制。目前,黑水虻是具有较多抗菌肽基因的昆虫之一,从中分离出包括天蚕素类和防御素类等多种抗菌肽物质,并验证了其抗菌活性[14]。Park等[15]研究表明,黑水虻体内的抗菌肽成分能够有效抑制金黄色葡萄球菌(*Staphylococcus aureus*)、大肠埃希氏菌(*Escherichia coli*)以及白色念珠菌(*Candida albicans*)等有害病原菌。夏嫱等[16]认为5龄期幼虫的抗逆性最强,经过诱导产生的抗菌肽具有更好的抑菌性、稳定性和冻融性。此外,黑水虻在不同培养基饲养条件下也可表达出不同含量和种类的抗菌肽[14],但关于黑水虻如何产生抗菌肽以及不同种类抗菌肽的作用机制尚不明确,亟需进一步深入研究。另一方面,目前暂无黑水虻抗菌肽在水产动物中的应用研究,这需要研究者开展相关评价工作。

2.3　月桂酸

月桂酸是黑水虻中的主要饱和脂肪酸,最高可占总脂肪酸的50%,具有良好的抗病毒、抗炎和杀菌的作用[17]。多数水产饲料原料中含少量或不含月桂酸,故黑水虻幼虫粉不仅可作为饲料中的蛋白质来源,虫油也是优质的脂肪源,其中月桂酸的抗菌作用可改善动物肠道微生物菌群组成和机体健康[18]。研究表明,黑水虻幼虫中的月桂酸是其自身合成,随着幼虫体质量增加而有所增加,并在足龄达到最高含量[19-20]。作为一种可再生资源,黑水虻凭借其自身可以合成月桂酸的特点,未来很有可能成为月桂酸的重要来源之一。目前,尚无使用月桂酸作为饲料添加剂在水产动物上的应用评估,而月桂酸的酯化物月桂酸单甘油酯已作为新型添加剂应用在食品和饲料等领域。

3　黑水虻在水产动物生产中的应用

3.1　肉食性鱼类

目前,黑水虻在肉食性鱼类中的应用包括海水鱼和淡水鱼两大类。

在珍珠龙胆石斑鱼(*Epinephelus fuscoguttatus* ♀×*E. lanceolatus* ♂)中,黑水虻替代鱼粉比例不宜

超过10%，替代量过多对其生长性能、饲料效率和肝脏、肠道健康均有负面影响，同时也会降低肠道菌群的总丰度以及肌肉品质[21]。与上述结果相似，斜带石斑鱼(*Epinephelus coioides*)基础饲料中虫粉替代10%鱼粉其生长与对照组无显著差异[22]。对大菱鲆(*Scophthalmus maximus*)的研究中，全脂和脱脂黑水虻幼虫粉可分别替代20%和30%鱼粉不会影响生长与生理功能[23-24]。Li等[25]研究认为，脱脂黑水虻替代不超过25%可提高半滑舌鳎(*Cynoglossus semilaevis*)生长性能、饲料利用以及肌肉品质。Mikołajczak等[26]研究表明，在大西洋鲑(*Salmo salar*)幼鱼阶段，脱脂黑水虻可替代29%鱼粉对其生长性能和肌肉品质无负面效果[27]。在大黄鱼(*Larimichthys crocea*)饲料中虫粉替代40%以下鱼粉比例对生长性能、体成分及健康状况无负面影响[28]；此外，黑水虻幼虫粉替代50%鱼粉未显著影响白梭吻鲈(*Sander lucioperca*)生长和全鱼营养组成[29]；替代50%鱼粉对金头鲷(*Sparus aurata*)生长、肠道消化酶、肠道形态学指标以及营养物质表观消化率无不利效应[30]；Abdel-Tawwab等[31]研究表明，用黑水虻幼虫粉替代50%鱼粉未对欧洲鲈(*Dicentrarchus labrax*)生长、饲料利用、体组成以及血液学指标产生负面作用。在日本花鲈(*Lateolabrax japonicus*)的研究中，虫粉替代64%鱼粉未对其生长性能、肝脏、肠道组织学形态以及抗氧化和免疫功能产生显著影响[32]。由上述研究可知，在海水肉食性鱼类中，黑水虻替代鱼粉的最适水平为10%～65%，这其中的差异与黑水虻虫粉的营养成分、鱼类不同生长阶段、饲料蛋白质及鱼粉水平等密切相关。例如，全脂虫粉中EPA和DHA等多不饱和脂肪酸低于鱼粉中的含量，对相关营养要求较高的鱼类，若替代量过多会导致营养失衡，进而引起一系列不良影响。

在淡水肉食性鱼中，Stejskal等[33]研究表明，用脱脂黑水虻幼虫粉替代鱼粉40%对河鲈(*Perca fluviatilis*)生长、饲料利用、体组成以及血液参数无显著影响。Dumas等[34]研究表明，黑水虻幼虫粉替代虹鳟(*Oncorhynchus mykiss*)饲料中50%鱼粉对其生长、饲料利用、蛋白质消化率以及肌肉营养组成和蛋白质沉积等指标无不良影响[35]。研究认为，黑水虻幼虫粉替代50%鱼粉未对线鳢(*Channa striata*)[36]、乌鳢(*Channa argus*)[37]和杂交鳢(*Channa argus*♂×*C. maculata*♀)[38]的生长和体组成产生负面效果，并可提高其抗氧化能力。在大口黑鲈(*Micropterus salmoides*)中，全脂黑水虻幼虫粉替代30%鱼粉对生长产生负面影响[39]，而脱脂黑水虻幼虫粉替代75%鱼粉未对生长有不利影响[40]，表明黑水虻中过高油脂以及其脂肪酸组成可能是影响其替代比例的因素。同时，Fischer等[41]研究表明，全脂黑水虻幼虫粉和预蛹粉替代66.7%鱼粉显著降低了大口黑鲈生长、饲料利用、摄食量、肌肉营养以及肠道健康成分，其中预蛹粉组的负面效果更大，推测可能是其中的甲壳素含量更高的原因。同时，大口黑鲈饲料中添加1%黑水虻虫浆可显著提高生长性能、抗病能力和强抗氧化活性，并促进肠道健康，说明虫浆也是一种比较优质的饲料原料形式[42]。

3.2　杂食性鱼类

黑水虻在杂食性鱼类的研究主要包括观赏鱼和食用鱼两大类。

斑马鱼(*Danio rerio*)是水产动物研究中主要的模式生物，同时也是一种常见的热带观赏鱼。Zarantoniello等[43]经过6个月的养殖试验结果表明，全脂黑水虻幼虫粉替代斑马鱼饲料中25%鱼粉未对其生长和肠道健康产生不利影响。而脱脂黑水虻幼虫粉完全替代鱼粉可改善斑马鱼生长、体长并调节生长、免疫和应激等相关基因表达[44]。石洪玥等[45]试验结果显示，用黑水虻幼虫活虫完全替代商品饲料，可显著提高锦鲤(*Cyprinus carpio*)的抗氧化能力，且活虫具有良好的诱食性。刘兴等[46]进一步用黑水虻虫粉替代锦鲤饲料中鱼粉，结果表明70%替代水平以下对其生长性能、体长以及肥满度无负面影响，同时可提高其抗氧化能力。同样，李景龙等[47]研究了黑水虻不同投喂策略对鹦鹉鱼(*Amphilophus*)生长及肠道消化酶的影响，结果表明最适投喂比例25%～50%(即3次饲料1次黑水虻和2次饲料2次黑水虻)对其生长和肠道消化酶无负面影响。同时，25%投喂比例可部分改善抗氧化能力和非特异性免疫指标，表明黑水虻幼虫具有替代人工配合饲料的可行性[48]。

在食用鱼方面，黑水虻在常见大宗淡水以及特种养殖品种中均有应用报道。肖扬波等[49]研究表明，用黑水虻幼虫粉替代合方鲫(*Carassis auratus*)饲料中40%鱼粉不影响其生长性能和体组成，在20%替代水平达到最大生长表现。Xu等[50]试验结果显示，黑水虻幼虫粉完全替代鱼粉对镜鲤(*Cyprinus carpio* var. *specularis*)生长、肠道消化酶、肌肉组成以及血清生化指标无显著影响，但从肠道健康角度最

适替代水平为75%。Zhou等[51]研究表明,黑水虻幼虫粉完全替代鱼粉对建鲤(*Cyprinus carpio* var. Jian)生长和体组成等指标无不利影响。在其他鲤品种中,黑水虻可替代50%的商品饲料,且对大盖巨脂鲤(*Colossoma macropomum*)生长无显著影响,并可提高鲤肌肉的品质和风味[52]。在特种杂食性淡水鱼方面,王国霞等[53]和陈晓瑛等[54]研究表明,全脂和脱脂黑水虻幼虫粉最高可替代30%和40%鱼粉,且对黄颡鱼(*Pelteobagrus fulvidraco*)生长性能、体组成以及血清生化指标无显著影响。研究表明,黑水虻替代最高60%鱼粉未对鳗鲶(*Pangasianodon hypophthalmus*)生长、消化酶活性和全鱼常规组成产生影响[55];替代75%以下鱼粉对革胡子鲶(*Clarias gariepinus*)幼鱼生长性能和健康状况无不利效果[56-57]。Kuo等[58]研究认为,脱脂黑水虻粉可替代75%鱼粉,且对日本鳗鲡(*Anguilla japonica*)生长性能无不利影响;Tippayadara等[59]研究表明,黑水虻幼虫粉完全替代鱼粉对尼罗罗非鱼(*Oreochromis niloticus*)生长、饲料利用和健康状态无显著影响;替代100%鱼粉对巴沙鱼(*Pangasius bocourti*)生长无显著影响,并可提高肌肉蛋白质和肝脏抗氧化能力以及肠道菌群多样性含量[60]。

上述研究表明,杂食性鱼类对黑水虻的替代鱼粉比例普遍高于肉食性鱼类。鱼的种类和肠道细菌的可利用性是鱼类利用几丁质酶降解和消化几丁质的决定因素[61],而这可能是两类不同食性鱼对黑水虻虫粉接受程度不同的因素之一。在关注黑水虻基础营养成分的同时,也需要注意其几丁质含量,这可能是影响虫粉在不同鱼种以及相同鱼种不同阶段应用效果的关键因素。

3.3 草食性鱼类

黑水虻在草食性水产动物中的应用较少,这可能与草食性鱼类饲料中动物性蛋白源用量少有关。Lu等[62]试验表明,脱脂黑水虻可完全替代饲料中豆粕,对草鱼(*Ctenopharyngodon idellus*)的生长性能、饲料利用以及肌肉营养成分无负面影响,且适当替代可提高机体抗氧化能力,但替代水平超过50%时,肠道消化酶和组织形态会产生不利效应。黄文庆等[63]研究认为,在草鱼饲料中用全脂黑水虻替代20%鱼粉可显著提高其生长性能和抗氧化能力,而超过40%后即产生不利影响。

3.4 甲壳动物

黑水虻在甲壳动物中的应用研究主要集中在凡纳滨对虾和青蟹。研究发现,凡纳滨对虾(*Litopenaeus vannamei*)对黑水虻幼虫粉的主要营养素表观消化率均超过肉骨粉和鸡肉粉等常用饲料中动物蛋白源,说明黑水虻是甲壳类动物的优质蛋白源[64]。He等[65]研究认为,用鲜黑水虻幼虫可替代最高50%的商品饲料,且对凡纳滨对虾生长性能、存活率以及消化酶活性和抗氧化酶活性无显著影响,过量替代会导致虾体肠道受损。胡俊茹等[66]研究表明,用黑水虻幼虫粉替代凡纳滨对虾幼虾饲料中15%鱼粉可显著改善其饲料效率,替代水平在15%~20%时可增强机体抗氧化能力。Chen等[67]研究表明,20%替代水平促进了脂质合成,而30%组削弱了β-氧化和糖酵解作用,并影响了不饱和脂肪酸的合成,这可能是影响虾的生长性能的原因之一。此外,10%替代量还提高了凡纳滨对虾肠道组织学特性以及副溶血性弧菌感染后的存活率[68]。然而,Richardson等[69]报道,黑水虻粉替代饲料中70%的鱼粉后仍可提高对虾生长性能,这可能与黑水虻质量、鱼粉含量以及配方组成等有关。黑水虻虫粉替代水产饲料中50%鱼粉可以显著改善拟穴青蟹(*Scylla paramamosain*)生长、成活率以及养殖水环境[70]。张文锐等[71]进一步用脱脂黑水虻替代青蟹饲料中的鱼粉,结果表明替代水平在25%~50%时青蟹具有更佳的肌肉脂肪酸组成。此外,黑水虻完全替代冰鲜鱼后可增强育肥期中华绒螯蟹的风味[72]。正常情况下,甲壳类动物能够产生降解几丁质的酶,故对饲料中的黑水虻虫粉有较强的耐受力,其最大添加量及应用效果也优于一般鱼类。

3.5 两栖爬行动物

目前已明确中华鳖、乌龟、牛蛙和美国青蛙等两栖爬行类动物可按照水生动物管理用于养殖和食用,但目前黑水虻只在中华鳖中有少量报道。Li等[73]研究表明,脱脂黑水虻粉替代10%的鱼粉可显著改善成鳖(*Pelodiscus sinensis*)的饲料利用率,且10%~15%替代组显著提高总抗氧化能力和谷胱甘肽过氧化物酶活性等抗氧化指标,以及蛋白质和氨基酸组成等肌肉营养价值;10%以下替代水平对幼鳖饲料利用、肠道消化酶活性、抗氧化能力和肌肉营养组成无负面影响[74]。

4 结语与展望

黑水虻在水产饲料中的应用研究主要集中在替代鱼粉、豆粕等主要蛋白源上。多数研究表明,黑水

虻的适量替代对水产动物生长性能、营养品质、肠道健康以及免疫功能等无不利影响，部分还具有改善作用。此外，由于水产饲料行业主要依赖鱼粉和豆粕作为主要饲料原料，给土地和水资源带来了巨大的环境压力，而黑水虻的生产对生态环境的负面影响较小。因此，黑水虻已被公认为传统蛋白质饲料的潜在替代品之一。此外，黑水虻中含有丰富的脂质，也是替代豆油和鱼油的潜在原料，目前关于虫油替代的报道较少，今后应加强相关方面的研究。

黑水虻完全应用到水产养殖中还面临一些挑战，例如质量问题和生物安全许可（监管问题）[75]。黑水虻的产品质量主要取决于培养基质，其成分会影响到蛋白质和脂肪等主要营养成分，以及几丁质、抗菌肽和月桂酸等活性成分[3]。因此，黑水虻产品进入市场应规范化、产业化，并明确相关标准。同时，我国对用于昆虫养殖的基质类型（包括黑水虻）并没有很严格的规定和限制，因为黑水虻可以有效分解和利用生活废弃物，所以培养基质的物理（塑料）和化学（抗生素/农药残留）成分也是至关重要。例如，塑料的生物转化（微塑料）也可能在黑水虻体内积累[76]。此外，当用作水生动物饲料原料时，加工方法也同样关键，不同加工技术制备的黑水虻在同一水产动物中会表现出不同的生长速度和饲料效率。当然，不同动物饲喂不同阶段产生的效果也有差异。因此，在今后的应用中还需进一步进行剂量、阶段等细化研究，制定出适用不同水产动物的使用标准。

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Progress on nutritional characteristics of black soldier fly larvae and its application in aquatic feeds

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Abstract Aquaculture is one of the most important ways of providing aquatic products, and the aquafeeds, especially for carnivorous aquatic animals, requires large amounts of fishmeal. To date, fishmeal has been recognized as the best source of protein in aquafeeds in terms of nutritional quality. However, with overfishing, anthropogenic activities and extreme weather, the production of major fish species that provide fishmeal has been decreasing globally year by year, leading to fishmeal shortage and price increase, and thus there is an urgent need for the aquaculture industry to seek for high quality alternative protein sources to fishmeal in order to achieve its sustainable development. Aquaculture is one of the most important ways of providing aquatic products. The aquatic feeds especially for carnivorous aquatic animals require large amounts of fishmeal. To date, fishmeal has been recognized as the best sources of protein in aquatic feeds in terms of nutritional quality. However, the production of major fish species that provide fishmeal has been decreasing globally year by year with overfishing, anthropogenic activities and extreme weather, leading to the shortage of fishmeal and the increase of its price, and thus there is an urgent need to seek the alternative sources of protein with high quality as fishmeal to achieve the sustainable development of aquaculture industry. Black soldier fly (BSF, *Hermetia illucens*) is a saprophytic insect, and its larvae have characteristics including wide feeding habits, strong reproductive ability, and rich and balanced nutrients. It is considered as a highly potential and new sources of feed protein and has broad prospects of application in the production of aquatic animals. This article reviewed the main nutritional and bioactive components of BSF larvae, as well as progress on their application in feeds for different aquaculture species such as herbivorous, omnivorous, carnivorous, crustacean, and amphibian reptiles. The optimal amount of BSF larvae in different aquatic feeds was summarized. The feasibility of using BSF larvae as a sustainable source of protein in aquatic feeds was explored. The problems and challenges in its practical application were analyzed. It will provide a basis and reference for developing and utilizing black soldier fly and studying its mechanism in aquatic animals.

Keywords black soldier fly (*Hermetia illucens*); nutritional characteristics; aquatic animals; new sources of protein; aquatic feeds

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