

黑水虻替代蛋白作为饲料的研究进展

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摘要 在全球人口增长和消费升级背景下, 动物蛋白饲料需求持续增加, 而鱼粉、豆粕等传统蛋白面临资源紧张和供应风险。黑水虻作为一种资源昆虫, 能够高效转化餐厨垃圾、畜禽粪便等有机废弃物, 产出富含优质蛋白和功能性脂质的虫体。本文系统综述黑水虻的营养学特征及其在水产、畜禽和宠物饲料中替代传统蛋白源的应用研究, 总结其对动物生长性能、免疫力和肠道健康的积极作用, 并指出其作为饲料原料所面临的挑战。未来研究应着重于品种选育、精准营养调控、加工工艺优化及安全性评估等方面, 以推动黑水虻蛋白饲料的规模化、安全化应用, 促进养殖业可持续发展。

关键词 黑水虻; 昆虫蛋白; 饲料原料; 替代蛋白; 肠道健康; 营养特征

Progress on black soldier fly as an alternative source of protein for feed

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Abstract The demand for animal protein feed continues to increase, while traditional proteins including fish meal and soybean meal face constraints of resource and risks of supply under the background of global population growth and consumption upgrading. The black soldier fly (*Hermetia illucens* L.), as a resource insect, can efficiently convert organic waste including food waste and livestock manure, producing larvae rich in high-quality protein and functional lipids. This article systematically reviewed the nutritional characteristics of black soldier fly larvae and its application in replacing traditional sources of protein in aquatic, livestock, and pet feed. Its positive effects on the growth performance, immunity, and intestinal health of animal were summarized. The challenges it faces as a feed ingredient were highlighted. Studies in the future should focus on the genetic improvement of strain, precision modulation of nutrition, optimization of processing techniques, and evaluation of safety to facilitate the large-scale, safe application of black soldier fly-derived protein in animal feed and promote sustainable development of the farming industry.

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Keywords black soldier fly (*Hermetia illucens* L.); insect protein; feed ingredients; alternative protein; intestinal health; nutritional characteristics

在全球人口增长与消费升级驱动下,动物性食品需求激增,养殖业面临优质蛋白饲料短缺的严峻挑战。传统核心蛋白源鱼粉与豆粕高度依赖进口,分别受制于渔业资源枯竭与耕地及供应不确定因素,对我国饲料产业构成“卡脖子”风险。原料供应紧张不仅推高养殖成本,而且威胁着产业链安全,因此,饲料行业亟需开发安全、高效、可持续的新型蛋白替代源。

黑水虻(*Hermetia illucens* L.)作为一种资源昆虫,因其高效的生物转化能力和丰富的营养价值而备受关注。黑水虻幼虫生长速率快、转化效率高,能将餐厨垃圾、畜禽粪便等有机废弃物转化为虫体物质,实现“变废为宝”^[1-5]。黑水虻虫粉粗蛋白含量高、氨基酸组成均衡,富含中链脂肪酸等活性成分,其综合营养价值比鱼粉与豆粕高,具有替代传统蛋白源的巨大潜力^[6-7]。

近年来,随着“减抗替抗”等政策的推进与产业绿色转型的需求,黑水虻蛋白作为一种具有功能特性的新型饲料原料,已在水产、畜禽及宠物饲料中展现出良好的替代潜力与健康促进效果^[8-10]。因此,本文系统综述黑水虻作为饲料蛋白源的营养学基础,及其在不同养殖动物中的应用效果,并展望推动黑水虻产业化进程的举措,以期为推动黑水虻饲料蛋白规模化应用提供科学依据,促进我国养殖业饲料自主化和绿色循环农业的发展。

1 黑水虻营养学特征

亮斑扁角水虻,俗称黑水虻(black soldier fly, BSF),属于双翅目水虻科扁角水虻属。黑水虻为完全变态发育生物,其生命周期需经历卵、幼虫、蛹和成虫4个发育阶段。幼虫期黑水虻具有食量大、食性杂、抗逆性强以及处理效率高等优点,适用于多种有机废弃物的处理。

黑水虻幼虫对于各类有机固废展现出极强的适应性,能够以餐厨垃圾、畜禽粪便、豆渣以及食用菌渣等多种有机固废为食。基质对于黑水虻的生长发育和营养指标有着显著的影响,在转化餐厨垃

圾、蔬菜废弃物及畜禽粪污等不同有机固废时,所得黑水虻虫粉的粗蛋白、粗脂肪和灰分含量存在较大波动,范围分别在30.93%~52.74%、1.50%~42.13%和12.85%~30.16%之间^[11]。通过脱除油脂的方式可以显著提高虫粉的蛋白质含量,脱脂虫粉的粗蛋白含量可达55.42%~65.50%,与鱼粉相当^[12]。

黑水虻虫粉氨基酸组成较为均衡,其氨基酸谱受基质的影响相对较小。与鱼粉和豆粕相比,虫粉多数必需氨基酸(如精氨酸、缬氨酸、苯丙氨酸、异亮氨酸和组氨酸)含量相近,但蛋氨酸、亮氨酸、苏氨酸及赖氨酸的含量通常低于鱼粉^[11,13]。黑水虻虫粉含有丰富的脂肪酸,中链脂肪酸占比超50%,其中月桂酸含量最高,油酸和亚油酸等不饱和脂肪酸含量高^[14]。此外,黑水虻虫粉含有丰富的微量元素,铜、铁以及锌等元素含量分别高达6.61~19.02、183.57~509.77、43.39~75.77 mg/kg,高于鱼粉和豆粕^[15]。

除常规营养成分以外,黑水虻虫粉中含有包括甲壳素、抗菌肽等在内的多种生物活性成分。甲壳素,又称几丁质,是一种广泛存在于昆虫和甲壳动物外壳中的一类天然多糖类高分子化合物。黑水虻各生命周期均含有甲壳素,其中蛹壳、成虫尸体甲壳素含量高,可用于甲壳素的提取^[16]。甲壳素可被肠道微生物降解为壳寡糖,少量的甲壳素可作为益生因子调节肠道健康,增强动物免疫力。向斑点叉尾鮰饲料中添加500 mg/kg的黑水虻甲壳素,可调节其肠道群落组成,增加益生菌的丰度^[17]。然而,甲壳素同样是一种已知的抗营养因子,过量摄入甲壳素会影响蛋白质等营养成分的消化吸收,并可能过度刺激肠道,从而引发炎症反应。黑水虻老熟幼虫、预蛹、蛹和成虫中甲壳素的含量为8%~24%,黑水虻虫粉添加量超过一定水平会降低养殖动物的生长性能和饲料利用率^[18-19]。通过甲壳素产生菌发酵黑水虻虫粉,可以获得低甲壳素并富含壳寡糖的黑水虻虫膏,具有更高的益生特征和营养特征^[20-21]。

抗菌肽是黑水虻虫体内另一特色生物活性组

分。由于长期生活在含有各种病原体的有机废弃物中,黑水虻演化出了极强的免疫系统,其基因组上编码抗菌肽的基因多达 50 个,是目前已知编码抗菌肽基因最多的昆虫,其中主要是天蚕素(cecropin)和防御素(defensins)^[22]。在水产养殖中,向饲料中添加富含抗菌肽的黑水虻虫粉,可提高养殖动物的生长性能、增强其免疫力并增强其抗病能力^[23-24]。在黑水虻的产业化进程中,酶解黑水虻虫浆作为一种高附加值产品受到越来越多的关注,利用微生物或酶将黑水虻的蛋白质等大分子物质水解成功能性小肽等活性物质,少量地应用于动物养殖即可发挥事半功倍的效果,成为“免疫增强剂+高效诱食剂+生长促进剂”多合一的高附加值饲料^[18,25-26]。

2 黑水虻作为饲料原料的应用

黑水虻产品在水产和禽畜领域中均有广泛的研究与应用,使用效果受加工方式、几丁质含量以及添加量等多种因素的影响。根据收获阶段与加工工艺的不同,黑水虻产品主要可以分为鲜虫、全脂虫粉、脱脂虫粉、预蛹粉、虫浆(鲜榨或酶解/发酵)以及虫油。在适宜的添加比例下,黑水虻产品对于养殖动物的生长性能、肠道健康以及免疫水平均有积极促进作用。

2.1 黑水虻在水产饲料中的应用

目前,黑水虻在水产饲料中的应用研究主要集中在肉食性鱼类和甲壳类动物,应用方式包括鲜虫、全脂虫粉、脱脂虫粉、预蛹粉、鲜榨虫浆、酶解发酵虫浆以及虫油。

在肉食性鱼类养殖中,由于日粮通常含有较高比例鱼粉,使用黑水虻虫粉替代饲料中的部分鱼粉存在较高的经济可行性。研究表明,一种由黑水虻脱脂虫粉、微藻粉和被囊动物粉完全替代鱼粉与鱼油的新型饲料,在金头鲷饲养中表现可行。该替代方案未对饲料利用率和生长性能产生负面影响,且能降低鱼肉脂质、减轻应激反应并改善肠道有益菌群^[27]。在黑水虻虫粉替代鱼粉后,欧洲鲈呈现出剂量依赖性的生理功能改善:包括以血清丙二醛水平升高为标志的抗氧化能力提升;吞噬活性与指数增强所代表的先天免疫激活;以及白细胞介素 1 β 和白细胞介素 10 基因表达上调所指示的特异性免疫调节。攻毒试验进一步证

实,此替代策略能显著提高鱼体的相对存活率,表明其在增强免疫保护力的同时未产生负面健康影响^[28]。在虹鳟、黄颡鱼等多种水产动物中,日粮内少量添加黑水虻虫粉替代部分鱼粉,对其生长性能与生理功能无显著影响;然而,替代比例过高则会抑制生长并损害肠道健康,其中,几丁质被认为是高比例替代时限制营养物质消化吸收的关键抗营养因子^[29-32]。

黑水虻在甲壳动物养殖中的应用研究主要集中在虾类。使用全脂黑水虻虫粉替代罗氏沼虾日粮中 20% 的鱼粉,对其存活率、生长性能、免疫力及应激反应均无不良影响,表明其可作为罗氏沼虾的安全饲料蛋白源^[33]。使用脱脂、全脂及酶解黑水虻虫粉少量替代南美白对虾日粮中的鱼粉,不仅对其生长性能无负面影响,还能调节其葡萄糖与脂质代谢,并增强抗病能力,展现出积极的营养调控作用^[34-36]。然而,在南美白对虾饲料中过高比例替代鱼粉会显著抑制其生长性能,并导致体成分(粗蛋白、粗脂肪及总磷)含量下降,但死亡率未受显著影响^[37]。在拟穴青蟹养殖中,黑水虻全脂或脱脂虫粉可替代高达 50% 的日粮,并能显著提升其生长性能、存活率及改善机体脂肪酸组成^[38-39]。

2.2 黑水虻在禽畜饲料中的应用

黑水虻是改善家禽生长性能、提高养殖经济效益、增加动物福利的优质昆虫饲料资源,可用于鱼粉和豆粕等原料的有效替代。

在家禽养殖业中,黑水虻虫粉的适量使用无论对肉鸡还是蛋鸡的生长性能和生产性能均有积极作用。使用黑水虻虫粉一定比例替代蛋鸡日粮中的豆粕,可提升产蛋量与蛋品质,并能优化蛋黄脂肪酸组成,显著增加多不饱和脂肪酸比例及 n-6/n-3 比值^[40]。在肉鸡养殖中,以 24% 的黑水虻虫粉替代豆粕可实现最佳生长性能,具体表现为平均日增重、胴体及胸肉产量显著提高,同时饲料转化率与肉质氧化稳定性也得到显著改善^[41]。

此外,黑水虻虫粉还可以作为功能性饲料通过增加有益活性物质的含量和优化肠道菌群结构等方式,提高鸡的抗病能力。在肉鸡日粮中添加 5% 黑水虻幼虫粉,不仅能改善其生长性能,还可通过增加有益短链脂肪酸、减轻炎症及优化肌脂组成来增强肠道抵抗力,且被证实对消化系统安全^[42]。在肉鸡日粮中添加 20% 黑水虻虫粉 42 d 后,可降低盲

肠微生物群的 β 多样性,具体表现为潜在病原菌普拉粪杆菌丰度下降,而益生菌毛螺菌属与脱卤杆菌属丰度上升。此调节作用在促进宿主健康的同时,未破坏菌群稳定性^[43]。

然而,随着养殖周期的延长或黑水虻虫粉替代比例的提高,蛋鸡的生产性能和肉鸡的生长性能会产生负面影响^[44-45]。造成这种结果的不一致的因素有很多,例如,虫粉中几丁质的累积会影响养殖动物蛋白质的消化效率,而养殖动物自身的生长性能会随着养殖周期的延长而出现下降。在其他禽类动物养殖方面,鹌鹑日粮中使用黑水虻虫粉替代 20% 的饲料,可显著降低料蛋比、改善肝肾功能与代谢水平,并增强其抗氧化与免疫性能。此外,该替代方案还能优化鹌鹑蛋的氨基酸与脂肪酸组成,从而全面提升生产性能与蛋品质量^[46]。

与家禽相比,黑水虻在猪、牛等家畜饲料中的应用研究相对有限,主要源于生理消化与食性差异。在猪养殖中,黑水虻的应用研究主要聚焦于其对生长性能的影响及其作为抗生素替代物的功能潜力。脱脂黑水虻虫粉可替代日粮中高达 50% 的鱼粉而不影响断奶仔猪生长性能;在养殖后期,脱脂虫粉添加水平与血液中葡萄糖、白蛋白及总蛋白浓度的线性增加相关,证实了黑水虻虫粉替代方案的可行性^[47]。全脂黑水虻虫粉还可作为功能性饲料,与复合益生菌协同替代饲用抗生素。该组合通过改善肠道健康、增强免疫与抗氧化功能,从而有效促进动物生长^[48]。此外,黑水虻虫油的消化能为 36.86 MJ/kg,与大豆油相当,其脂肪酸组成以中链脂肪酸为主,月桂酸含量最高,且富含不饱和脂肪酸,表明其作为一种潜在的猪饲料脂肪来源的前景^[49]。

在牛养殖中,黑水虻的应用研究主要聚焦于替代豆粕等传统蛋白源的潜力、对瘤胃发酵的调节作用,以及在减少抗生素使用方面的功效。在肉牛养殖中,使用颗粒或粉状黑水虻虫粉替代日粮豆粕均可提高蛋白质消化率,其中以颗粒形式替代 25% 时效果最佳,能在维持瘤胃稳态的同时,最大程度地提升营养物质消化率^[50]。在泌乳奶牛日粮中使用脱脂黑水虻幼虫粉替代最高 100% 的豆粕,不会降低产奶量、乳品质及氮利用效率,并能显著提高纤维类物质的消化率,表明其具备完全替代豆粕作为奶牛蛋白饲料的潜力^[51]。

此外,减少瘤胃甲烷排放是当前反刍动物营养研究的重要方向之一,主要的方式包括优化饲料配方以及调控瘤胃发酵等。在肉牛和泌乳奶牛饲料中添加少量黑水虻虫油,可在不影响瘤胃基础健康的前提下,提高养分消化率、增加有益短链脂肪酸产量,并显著降低原虫数量、甲烷排放及产甲烷菌丰度,表明其是一种潜力巨大的功能性饲料添加剂^[52-53]。

2.3 黑水虻在宠物饲料中的应用

随着近年来宠物食品市场规模持续扩大,开发高质量、可持续和功能性的饲料产品已成为宠物食品行业的重要研究方向。黑水虻因蛋白含量高、必需氨基酸模式优、消化率高以及富含多种活性物质等特点,已被美国饲料管理协会(AAFCO)列入犬/猫全价饲料可用原料清单。全球已经涌现 Protix、Ynsect 等多家黑水虻宠物饲料公司,据统计,2024 年市场规模大约为 2.43 亿美元,预计到 2031 年将超过 13 亿美元^[54]。在宠物饲料中,黑水虻常以虫干、全脂虫粉、脱脂虫粉及虫油等形式应用,用以替代配方中的鸡肉粉、鱼粉或棕榈油等传统原料。目前,针对黑水虻相关产品已经在犬粮和猫粮中关于适口性、功能性以及低致敏性开展了大量研究。

在犬粮中的应用研究表明,黑水虻虫粉和虫油可作为犬饲料中鸡粉和油脂的有效替代或补充蛋白源。使用 8% 的黑水虻虫油替代比格犬犬粮中的油脂,对其体重、体况、抗氧化能力、营养物质消化率、粪便短链脂肪酸(SCFAs)和菌群结构等方面均无显著差异,表明对犬只没有产生任何显著的不良影响^[55]。在以较高比例使用黑水虻幼虫脱脂虫粉替代犬粮中的鸡肉粉时,不仅未对犬只造成负面影响,反而显示出一个“功能性蛋白质源”的作用,能显著提升皮肤屏障功能,减少水分流失,增加皮肤湿度^[56]。

老年犬只常伴随多种健康问题,对犬粮的要求较高,在犬粮中使用低比例的黑水虻虫粉,不仅能保证老年犬只的基本健康,还可能带来辅助降低胆固醇的额外健康益处^[57]。常规犬粮中的鸡肉粉、鱼粉等含有多种致敏蛋白,可能导致犬只出现过敏等不良反应,而黑水虻虫粉的一个重要优势在于其低致敏特性。使用黑水虻脱脂虫粉作为已有过敏反应的患病犬只的唯一蛋白来源,对其生

理生化指标不会产生不利影响,且没有加重核心过敏症,表明了黑水虻虫粉用于开发低过敏犬粮的可行性^[58]。此外,酶解黑水虻虫浆在抗关节炎方面有巨大潜力,虫浆中含有具有修复软骨功能的葡萄糖胺,且能够显著抑制免疫细胞活性氧的产生^[59]。

黑水虻虫粉在猫粮中的应用研究也取得了许多实质性进展,证实了其积极效果。蛋白质是构成猫粮中最主要的成分,幼猫、成年猫以及孕期母猫对于蛋白质的需求量不同,使用全脂或脱脂黑水虻作为不同阶段的猫的蛋白源均会对猫产生积极影响。在日粮中添加黑水虻虫粉可显著促进幼猫的体重增长,同时改善其免疫指标并增强抗氧化能力^[60]。对于成年猫猫粮而言,适口性与蛋白质源的选择至关重要。在猫粮中添加 20% 的黑水虻全脂虫粉,可对成年猫的后肠产生积极的影响,能够显著提高粪便评分,促进后肠的有益代谢并调节肠道菌群结构,对血液代谢物和免疫标记物等其他健康指标无负面影响^[61]。

不同基质饲养的黑水虻对于猫的营养消化会产生影响。研究表明,动物基质饲养的黑水虻虫粉组的粗蛋白消化率和首次嗅探次数均显著高于植物基质饲养的黑水虻虫粉组,表明动物基质饲养的黑水虻虫粉在消化率和适口性上的表现优于植物基质^[62]。黑水虻适用于猫的所有生命阶段,包括繁殖和生长发育的关键期。以 20% 比例的黑水虻虫粉替代怀孕和哺乳期母猫日粮中的蛋白源,未对母猫在产仔数、采食量、体重和粪便质量方面产生负面影响,同时显著提升了新生幼猫的体重和采食量,并提升了粗蛋白和氨基酸的消化率^[63]。

3 结语与展望

黑水虻作为一种高效转化有机废弃物的资源昆虫,虫体营养价值高,富含优质蛋白、功能性脂质及多种生物活性物质,具有替代鱼粉、豆粕等传统蛋白源的巨大潜力^[64]。在水产、畜禽及宠物饲料中适量添加黑水虻产品对动物生长性能、免疫力、肠道健康及产品品质具有积极影响。目前,农业农村部已将黑水虻纳入《饲料原料目录》,允许在不影响公共健康和动物健康的前提下,作为饲料蛋白资源在饲料生产和养殖中使用。黑水虻作为新型饲料蛋白源前景十分广阔,但其产业化和大

规模应用刚处于起步阶段,发展过程中仍面临多重挑战:虫体营养成分受基质影响显著,产品质量稳定性较低;加工工艺成本较高,加工过程活性成分损失等。

为了发挥黑水虻作为新型饲料原料的优势,推进黑水虻饲料的规模化、安全化应用,根据国内外研究和产业化发展现状,未来研究应聚焦以下方向:

1) 品种选育与改良。结合遗传选育与微生物组技术,培育高产、高营养、广适性的优良黑水虻品系。

2) 营养精准调控。深入研究物料对虫体营养影响的机制,开发定向营养调控技术,实现黑水虻产品标准化。

3) 加工工艺创新。研发高效、低成本的干燥、脱脂及活性成分提取工艺,提高产品附加值。

4) 安全与风险评估体系建立。构建覆盖原料、生产过程至终产品的全链条安全监测与评估体系,确保黑水虻产品的安全性。

5) 功能活性物质深度开发。加强抗菌肽、中链脂肪酸、几丁质及其衍生物等活性成分的功能研究,开发专用功能性黑水虻饲料。

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