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黑水虻应用研究进展

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摘要： 黑水虻 *Hermetia illucens* L.原产于美洲，在世界范围内广泛分布，具有产卵量大、生长速度快等特点。黑水虻幼虫可以将废弃物高效地转化为自身营养物质，其预蛹营养价值较高。黑水虻幼虫体内含有丰富的蛋白质、脂肪及抗菌肽等物质，以其幼虫饲喂动物具有增强体质、提高免疫力、预防疾病等功能，是极具经济价值的资源昆虫。本文综述了黑水虻生物转化处理废弃物、饲料蛋白应用、油脂资源开发、肠道抗菌肽应用等研究进展，并就实际应用过程中应关注的问题进行了讨论，旨在为黑水虻高效利用提供参考。

关键词： 黑水虻；农业有机废弃物；饲料蛋白；生物柴油；抗菌肽
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Research progress on the application of black soldier fly (*Hermetia illucens* L.)

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Abstract: The black soldier fly (*Hermetia illucens* L.) is native to the Americas and widely distributed worldwide. It has the characteristics of large egg production and fast growth rate. *H. illucens* larvae can convert waste into their own nutrients efficiently, and the nutritional value in prepupa is high. The body of black soldier fly larvae is rich in protein, fat, and antimicrobial peptides. As a high economical valuable resource insects, *H. illucens* larvae can enhance physical fitness, improve immunity, and prevent diseases when used as animal feed. This article reviewed the research progress of waste biotransformation, feed protein application, oil resources development, intestinal antimicrobial peptides from *H. illucens*. In addition, key issues in practical application were also discussed, aiming to provide reference for the efficient utilization of *H. illucens*.

Key words: Black water fly; agricultural organic waste; feed protein; biodiesel; antibacterial peptides

黑水虻 *Hermetia illucens* L.学名为亮斑扁角水虻，属于昆虫纲双翅目水虻科扁角水虻属，其生长发育过程包含卵期、幼虫期、预蛹期、蛹期和成虫期，世代历期约35 d。黑水虻种群扩展能力

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较强，具有产卵量大、发育时间短、幼虫存活率高等生物学优势。黑水虻耐受性良好，在转化处理厨余垃圾等领域具有极大潜力，能够将有机废弃物转化为有机肥、饲料和燃料，实现有机废弃物的处理和再利用，养殖黑水虻已成为国内的新兴农业项目（Surendra *et al.*，2020；杨均等，2023）。黑水虻营养价值丰富，体内含有大量的蛋白质和脂肪，每100 g幼虫干粉中粗蛋白含量高达47%~50%，脂肪含量24%~22%，含有微生物、矿物质等必需营养素，被认为是最有潜力替代饲料中鱼粉的蛋白源之一。目前黑水虻养殖主要以工厂化的形式实现养殖的产业化和规模化，其主要技术包括原料的预处理、虫卵孵化与接种、幼虫半自动化养殖、鲜虫分筛后处理、种蛹管理、成虫诱卵。本文从黑水虻生物转化处理废弃物、饲料蛋白应用、油脂资源开发、肠道抗菌肽等影响四方面，综述了当前国内外黑水虻应用研究进展，并对黑水虻应用需要关注的问题作了讨论，旨在为黑水虻产品工厂化生产和产业化应用提供参考资料。

1 黑水虻生物转化处理有机废弃物

畜禽粪便和生活垃圾处理已成为世界难题，传统方法处理具有能源消耗高、处理效果不佳、产品效益较差等缺点（胡法挺，2023）。黑水虻可以取食禽畜养殖产生的粪便以及各种生活垃圾，将废弃物转化为蛋白质、多肽以及油脂，用于畜禽饲料、医药合成等领域（Liu *et al.*，2019），在生物转化处理废弃物领域具有广阔的应用前景（陈奕珊等，2023）。与传统方法相比，黑水虻可在短时间内将有机废物的重量减少50%（Amrul *et al.*，2022）。

1.1 黑水虻生物转化的效益

黑水虻生物转化农业有机废弃物具有低能耗、环境友好、绿色环保等优点。黑水虻能够将玉米秸秆转化为新型有机肥料，黑水虻处理后的猪粪可以作为良好的有机肥使用。黑水虻幼虫可高效处理猪粪，虫粉加工为蛋鸡饲料，提升产蛋性能（谢久凤等，2023；钟鲁龙等，2023）。黑水虻对猪粪的转化效率高于牛粪，幼虫产量更高，且具有减少甲烷排放的功能（Matos *et al.*，2021）。黑水虻对发酵大麦废物转化力良好，且预蛹蛋白质含量较高（Permana *et al.*，2021）。黑水虻转化处理湿垃圾效率显著高于好氧堆肥，且虫粪具有良好的营养价值（马聪，2023）。

黑水虻在环境保护方面也具有广泛的应用价值。黑水虻幼虫能够显著降低猪粪中的病原体丰度，减少猪粪中重金属浓度（Wu *et al.*，2021）。以添加重金属的饲料饲喂黑水虻，其体内重金属含量显著低于饲料中重金属含量，且黑水虻的发育速率未出现显著下降（Diener *et al.*，2015）。此外，黑水虻幼虫被广泛用于处理污水厂污泥，具有处理成本低、技术难度小、设备要求少等优势（强敬雯等，2023）。饲喂城市污水污泥对黑水虻幼虫存活率无显著影响（Arnone *et al.*，2021），同时可减少有机废弃物发酵产生的硫化氢等气体，对环境保护具有积极作用（马聪，2023）。黑水虻具有转化处理金霉素菌渣的功能，对金霉素的降解速率与其初始浓度密切相关（王会，2023）。

1.2 饲喂基质对黑水虻生物转化的影响

饲料种类及组成对黑水虻生长发育及营养物质含量具有重要影响。以泔水饲养的黑水虻幼虫生长速率和干物质含量最高，约为鸡饲料基质饲喂黑水虻幼虫的2倍（Veldkamp *et al.*，2021）。饲喂低纤维素、高蛋白的甜菜废丝能够有效提升黑水虻幼虫转化率（刘文盈等，2023）。饲喂蟑螂排泄物可以提升黑水虻幼虫的发育速率和单虫重量（Jucker *et al.*，2020）。饲喂发酵后的餐厨垃圾能够有效促进黑水虻幼虫的粗脂肪积累（何卓君等，2023）。金宁等（2023）研究表明，使用碳氮比21：1的餐厨垃圾饲喂黑水虻，其碳元素和氮元素资源化效率、生物转化率、虫产率显著提升。麦力文等（2023）发现，使用碳氮比为11.52的鸡粪饲喂的黑水虻生物转化效率和蛋白含量呈现上升趋势。何卓君等（2023）研究表明，饲喂农作物秸秆时，黑水虻生长发育和转化餐厨垃圾效率显著增强。饲喂橙子、香蕉皮与75%鱼类排泄废物混合物的黑水虻幼虫生物转化效率提高（Isibika *et al.*，2021）。饲喂青贮草和屠宰废物混合物的黑水虻幼虫生物转化效率显著上升（Deen *et al.*，2023）。饲喂豆腐渣和厨余垃圾混合物的幼虫脂质含量以及生物转化效率增加（Li *et al.*，2021）。棕榈油果串、棕榈仁粉饲喂的黑水虻幼虫发育速度和重量呈上升趋势（Kluber *et al.*，2022）。饲喂稻草时，黑水虻幼虫发育时间缩短，且预蛹干重增加

(Manurung *et al.*, 2016)。饲喂食物垃圾和未腐熟堆肥混合物的黑水虻幼虫体重增加，蛋白质含量提升（Fadhillah *et al.*, 2020）。使用食用油、发酵微生物、干餐厨垃圾和鸡粪混合物饲喂黑水虻，对黑水虻幼虫的干重量和油脂含量具有积极作用（Lee *et al.*, 2021）。以富含n-3系列高不饱和脂肪酸的裂殖壶藻渣饲喂黑水虻，其油脂中n-3系列多不饱和脂肪酸、二十碳五烯酸和二十二碳六烯酸含量显著提升（徐歆歆，2022）。

1.3 黑水虻肠道微生物对生物转化的影响

黑水虻肠道共生菌有助于促进其幼虫生长（Callegari *et al.*, 2020）。黑水虻肠道共生菌能够促进几丁质与纤维素分解及磷酸盐溶解（Tamrela *et al.*, 2020）。黑水虻体内的纤维单胞菌、肠球菌等能够降解木质纤维素（Kluber *et al.*, 2022）。以黑水虻体内高活性菌株处理后的猪粪饲喂黑水虻，可显著提升化蛹速率和预蛹重量（燕洋洋，2023）。黑水虻肠道共生菌能够增强幼虫对餐厨垃圾的生物降解功能（Jiang *et al.*, 2019）。

全球黑水虻种群之间的遗传多样性具有地理学系统发育差异，肠道微生物多样性也具有差异（Khamis *et al.*, 2020）。黑水虻体内菌株群落分析表明，优势菌株变形菌门占66.3%，厚壁菌门占30.2%、拟杆菌门占2.9%，放线菌门占0.6%（Gorrens *et al.*, 2021）。适宜的饲养环境和饲料种类能够显著提升黑水虻肠道微生物的种类和数量（谢久凤等，2023）。

2 黑水虻虫粉作为饲料替代蛋白源

目前世界范围内鱼粉和豆粕产量呈现下降趋势，出现了价格上涨和供应不稳定等现象，急需能够替代鱼粉和豆粕等传统原料，且具有高营养、低成本、可持续等特征的新型蛋白来源（吉红等，2023）。黑水虻幼虫体内蛋白质含量较高，其粗蛋白含量达到47%~50%，与水生和畜禽动物相当，且含有丰富的维生素、矿物质和氨基酸等多种生物活性成分，可作为水产和畜禽养殖领域中鱼粉和豆粕的良好替代品（张慧洁等，2024）。

2.1 黑水虻虫粉替代畜禽饲料蛋白源

黑水虻虫粉是养殖领域中良好的替代饲料，具有营养价值丰富、价格低廉等优点，但目前仅应用于鸡鸭等少数家禽品种。赵燕等（2023）研究发现，在蛋鸡饲料中使用黑水虻虫粉替代豆粕，能够提升蛋鸡的抗氧化能力、免疫水平和生殖激素水平。在雪峰乌骨鸡饲料中添加3%的黑水虻虫粉，可以有效提升蛋鸡的生产性能、抗氧化能力和免疫功能（Liu *et al.*, 2021）。将黑水虻虫粉与蜂胶混合物加入肉鸡饲料，肉鸡的生长速度和鸡肉品质显著提升（Kinasih *et al.*, 2018）。在肉鸡饲料中加入脱脂黑水虻虫粉，能够提升肉鸡营养消化速率及可消化氨基酸含量（Schiavone *et al.*, 2017）。将黑水虻虫粉加入建水黄褐鸭饲料，鸭肉品质及氨基酸含量、产蛋量显著提升（鲍晓伟等，2023）。以黑水虻饲喂鹌鹑时，其脂肪酸和脂质含量显著增高（Cullere *et al.*, 2019）。将15%的脱脂黑水虻虫粉加入鹌鹑饲粮中，鹌鹑蛋内的饱和脂肪酸含量增加（Zotte *et al.*, 2019）。

在奶牛饲料中添加10 g/头/天和100 g/头/天的黑水虻虫粉，能够显著增强奶牛的免疫力及牛奶产量（Nekrasov *et al.*, 2022）。在断奶仔猪饲料中添加含量为12%的黑水虻虫粉时，仔猪生长性能、营养物质利用率及抗氧化能力呈现上升趋势，肠道炎症发病率显著减少（Boontiam *et al.*, 2022）。

2.2 黑水虻虫粉替代水产饲料蛋白源

在水产饲料中添加适宜比例的黑水虻虫粉替代鱼粉，具有提高生产性能和免疫力等优点，是鱼类养殖领域优质蛋白质的稳定来源。肖杨波等（2023）发现，在饲料中添加20%的黑水虻虫粉替代鱼粉，合方鲫的生长速率显著提升。使用黑水虻虫粉饲喂鲑鱼，能够提升鲑鱼的生产性能及其对蛋白质、氨基酸的消化率（Papuc *et al.*, 2020）。在鳟鱼饲料中添加黑水虻虫粉，鳟鱼背部鱼片干物质和粗脂肪含量呈上升趋势（Renna *et al.*, 2017）。黄颡鱼饲料中添加含量30%的黑水虫粉，黄颡鱼血清指标、鱼肉粗蛋白含量、必需氨基酸和呈味氨基酸含量显著上升（蔺玉珍等，2023）。在斑马鱼饲料中添加黑水虻虫粉替代鱼粉，能够增强其体内酶活性（Fronte *et al.*, 2021）。在克氏原螯虾饲料中添加34.25%的黑水虻虫粉替代鱼粉，克氏原螯虾的生长性能、机体免疫能力及部分血淋巴免疫酶活性显著提升（韩光明等，2023）。在梭鱼饲料中添加含量30%的黑水虻虫粉，梭鱼免疫相关基因表达呈升高趋势（Hender *et al.*, 2021）。用富含螺旋藻的咖啡银皮饲喂的黑水虻幼虫体内脂类和生物活性分子数量增加，其饲喂的

虹鳟鱼免疫基因表达量增加（Ratti *et al.*，2023）。在大菱鲆饲料中添加20%含量的全脂黑水虻虫粉替代鱼粉，能够显著提升大菱鲆的抗氧化能力（贲玲芝等，2022）。使用黑水虻虫粉替代金头鲷蔬菜型饲料中的植物蛋白成分，有助于改善金头鲷肠道健康状况（Randazzo *et al.*，2021）。黑水虻虫粉单独或与家禽副产品粉混合添加在欧洲鲈鱼饲料中，可显著提高其肠道消化吸收功能（Pleic *et al.*，2022）。在尼罗罗非鱼 *Oreochromis niloticus* 饲料中添加75%含量的黑水虻虫粉替代鱼粉，能够显著改善尼罗罗非鱼鱼苗的生长性能，促进其肝脏和肠道器官健康，饲料损耗率降低30%（Limbu *et al.*，2022）。使用黑水虻虫粉饲喂虹鳟鱼，可显著增加肠道乳酸菌丰度和微生多样性（Terova *et al.*，2019；Rimoldl *et al.*，2021）。在黄鳝饲料中添加黑水虻虫粉替代鱼粉，可对黄鳝的生长性能和肠道菌群平衡产生积极作用（Hu *et al.*，2020）。

3 黑水虻幼虫油脂开发利用

黑水虻油脂理化性质分析表明，黑水虻幼虫油酸价及其过氧化值都低于饲料中常使用的猪油、豆油等国际上的饲用油脂标准（徐歆歆等，2022）。黑水虻脂肪含量高达22%~24%，具有促进肠道健康和生长性能，以及提高抗氧化、免疫能力和调节脂质代谢的作用，是饲料中一种潜在油源。黑水虻幼虫体内的脂肪含量高、饱和脂肪酸和不饱和脂肪酸的比例合适，可用于开发航空、工业和农业领域用油（袁海林等，2023）。

3.1 黑水虻幼虫油脂用于畜禽水产饲料

黑水虻油脂用于饲料可有效提高畜禽水产的生长速度和营养价值。在肉鸡饲料中使用黑水虻幼虫油脂代替大豆油，能够提升生产性能和鸡肉品质（Murawska *et al.*，2021；Schafer *et al.*，2023）。在肉鸡饲料中添加黑水虻幼虫油脂，肉鸡体内饱和脂肪酸含量增加（Cullere *et al.*，2019）。在猪饲料中添加黑水虻幼虫油脂，可以提升保育猪饲料利用率和生长性能（Heugten *et al.*，2022）。以黑水虻幼虫油脂替代豆油，可有效提高血鹦鹉鱼免疫力和生长发育速度（石洪玥等，2020）。黑水虻幼虫油脂含有丰富的油酸、月桂酸等营养物质，添加在饲料中能显著提高罗非鱼生长性能（Bakar *et al.*，2021）。在淇河鲫饲料中添加黑水虻油脂替代豆油，可显著提升淇河鲫的消化酶活性和抗氧化能力（贾申宗等，2022）。在黄颡鱼饲料中添加黑水虻幼虫油脂，能够提高黄颡鱼抗氧化能力和消费酶活性（胡俊茹等，2020）。

黑水虻油脂可有效提高畜禽水产的免疫力和抗病性。以黑水虻幼虫油脂替代用于草鱼饲料的大豆油，能够显著提高草鱼肠道菌群的多样性和丰度及抗氧化能力（陈延娜等，2019）。黑水虻幼虫油脂取代肉鸡饲料的大豆油，能够增加肉鸡盲肠中丹毒荚膜菌属的丰度（Kim *et al.*，2020）。在仔猪饲料中添加2%的黑水虻幼虫油脂，可将仔猪腹泻率降低10%（肖琛闻等，2023）。以蔬菜饲喂黑水虻幼虫时，其油脂具有良好的抑菌特性（Saviane *et al.*，2021）。

3.2 黑水虻幼虫油脂开发生物柴油

使用硫酸作为催化剂，在甲醇中通过酯交换反应，能够将黑水虻幼虫脂质合成为脂肪酸甲酯生物柴油（Leong *et al.*，2016）。在柴油燃料中添加黑水油脂，混合后柴油燃料的密度、闪点和粘度、十六烷值显著提升（Yusaf *et al.*，2022）。将黑水虻幼虫油和柴油作为混合燃料，发动机的氮氧排化物排放量呈下降趋势（Kamarulzaman *et al.*，2019）。以6.43%黑水虻幼虫油与93.57%柴油混合作为发动机燃料，发动机性能达到最大值（Kamarulzaman *et al.*，2020）。

3.3 黑水虻幼虫油脂的其他应用

黑水虻油脂在工业领域中应用广泛。黑水虻粗油脂可作为润滑油的添加剂，虫体油脂衍生物有助于形成润滑保护膜，显著提升油品的摩擦学性能（吴晗等，2024）。通过硫化反应和酯交换反应，以黑水虻幼虫油脂制备的润滑油，能显著增加摩擦学性能、黏温性能及氧化稳定性（向志雄等，2023）。通过酶促甘油解，能够利用黑水虻幼虫油脂制备单酰甘油（Xu *et al.*，2021）。

4 黑水虻幼虫提取肠道抗菌肽

目前动物饲料中已被严令禁止加入抗生素，急需开发抗生素的替代品。昆虫免疫系统产生的抗菌肽，具有良好抑菌性，具有替代抗生素的潜能（章启慧等，2022）。黑水虻幼虫体内具有丰富的抗菌肽，可激活宿主的防御系统，杀死病原体

（胡霞等，2022）。黑水虻幼虫体内含有多种生物活性物质，如几丁质等，饲喂黑水虻幼虫的动物肠道内菌群丰度显著提升（仲崇华等，2022）。

4.1 黑水虻幼虫抗菌肽的应用价值

抗菌肽具有广谱的抗菌活性，对能够有效的杀伤细菌，特别是其对某些耐药性病原菌的高效杀灭作用引起了广泛关注。黑水虻体内含有丰富的广谱性抗菌肽，能够对多种微生物产生抑菌作用，具有作为抗生素替代品的潜能（Elhag *et al.*，2017）。饲粮中添加植物油、混合菌液的黑水虻幼虫体内抗菌肽的活性显著提升（胡漂琪等，2022）。使用大肠杆菌和金黄球菌菌液诱导黑水虻幼虫，可以诱导抗菌肽大量的生成（陈燕等，2023）。

某些抗菌肽对部分癌细胞、原虫、病毒和真菌等有杀灭作用，甚至能加速伤口愈合过程和提高免疫力水平。黑水虻幼虫抗菌肽可以防治沙门氏菌的侵染（Lee *et al.*，2020）。黑水虻抗菌肽粗提取物（0.25 mg/L）对曲霉和沙门氏菌具有良好的抑菌效果（张飞骏等，2023）。黑水虻抗菌肽能够有效降低大肠杆菌、鼠伤寒沙门氏菌等病原菌活性（Auza *et al.*，2020）。黑水虻HI-3抗菌肽具有调控RAW264.7细胞免疫的功能，RAW264.7细胞的抗氧化能力和吞噬能力随着抗菌肽浓度增加而显著提升（许晓燕等，2023）。黑水虻体内的HI-3抗菌肽能够促进结肠癌HCT-8细胞的凋亡（冯群等，2023）。

5 研究与展望

黑水虻作为一种新型资源昆虫，具有很好的生物能源开发、生物转化、饲料替代潜能，其体内抗菌肽在医疗领域表现出广阔的应用前景，受到了产业界的广泛关注。但值得注意的是，目前黑水虻产业化应用和生产过程中还存在着许多需要关注的问题。

目前黑水虻幼虫粉在畜禽和水产饲料中被作为蛋白源广泛使用，可用于烘焙食品和开发保健产品，且不会对人体产生不良影响（Montevecchi *et al.*，2021）。生产应用中仍存在一定的局限性。肉鸡饲料中添加黑水虻虫粉比例过高，会显著降低肉鸡的生长性能、肉质和口感，也会对增加黄褐鸭肝脏代谢功能负担（鲍晓伟等，2022），因此，在鸡鸭饲料中添加黑水虻虫粉量需要进一步测定。黑水虻安全毒理性实验表明，经普通方法处理的黑水虻食品内含有少量毒素，只有经严格清杂技术处理的黑水虻方能作为食品。黑水虻幼虫体内能够检测出沙门氏菌和蜡状芽孢杆菌沙门等病原体，黑水虻虫粉添加在食品中的安全性有待于进一步确认，虫粉灭菌净化等相关研究有待加强（Wynants *et al.*，2019）。

黑水虻油脂被作为辅料广泛添加于饲料中，可用于开发生物燃油和柴油添加剂。但黑水虻油脂在饲料中的大量应用，会导致禽畜和水产的腹脂堆积，肌肉品质下降。柴油燃料中添加黑水虻油脂比例过高，会显著降低柴油的燃烧性能和增加氮氧排放量，因此在柴油燃料中添加黑水虻油脂量需要进一步测定。

黑水虻规模化养殖造成的环保问题需要引起重视。规模化养殖黑水虻转化处理废弃物可能产生臭味气体，生活环境和饲养基质也可能导致黑水虻生物转化效率产生波动。筛选适宜的饲喂基质和饲养环境，有助于减少环境污染，提高黑水虻生物转化效率。黑水虻肠道提取物内的α-半乳糖苷酶、β-半乳糖苷酶有助于其幼虫高效转化处理餐厨垃圾等废弃物，减少污染排放和促进环境可持续发展（Kim *et al.*，2011）。

黑水虻通过免疫系统基因调节其肠道微生物，产生数量众多的抑菌分子，如抗菌肽和新型酶等，抑制许多人畜共同患的病原体（Smet *et al.*，2018；Huang *et al.*，2020）。黑水虻抗菌肽能够减少结肠癌细胞的数量，可以作为治疗癌症的新型手段，但黑水虻抗菌肽提取工艺设备复杂，生物活性受环境影响大，抗菌肽制作工艺亟待改进。

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