



黄粉虫开发利用研究进展*

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摘要 本文综述了近年来黄粉虫 *Tenebrio molitor* 在国内外的利用研究进展。对黄粉虫在动物生产、食品应用、营养开发与利用、环境保护及农业生产等方面研究成果进行归纳总结。以期为同领域的深入研究和未来产业化发展提供参考。

关键词 黄粉虫; 动物生产; 食品应用; 营养开发; 环境保护; 农业生产

Advances in the development and utilization of the yellow mealworm

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Abstract This paper reviews the commercial utilization of the yellow mealworm, *Tenebrio molitor*, both domestically and internationally, over recent years. It summarizes advances in mealworm production, nutrition, utilization in animal feed and environmental protection, providing a reference for future research in this field.

Key words *Tenebrio molitor*; animal production; food applications; nutrition development; environmental protection; agricultural production

随着全球人口稳步增长和平均生活水平不断提高,人类饮食中动物蛋白比例不断增大;而全球耕地资源和水资源的不断消耗却导致传统蛋白资源日益匮乏(Sandra *et al.*, 2020)。人类迫切需要开发新兴蛋白资源以脱离困境(Arnold *et al.*, 2017)。昆虫作为地球上数量最多、分布最广、种类最丰富的物种,蕴含的生物资源超乎想象。直到21世纪初,人类已知昆虫种类依旧非常有限,昆虫对人类健康以及农业生产的影响超乎想象(陈瑜和马春森, 2010)。黄粉虫属鞘翅目,是一种仓储昆虫,俗称面包虫。黄粉虫因其独特营养学特性而成为昆虫蛋白资源中的佼佼者(杨兆芬等, 1999),故近年来关于黄粉虫资源利用研究成果不断涌现。本文综合介绍了黄粉虫近年来在国内外利用研究的进展,对黄粉虫

在动物生产、食品应用、环境保护、营养开发及农业生产等方面研究成果进行归纳总结,同时对研究过程中发现的问题进行客观评述,以期为同领域研究开拓视野,推动昆虫相关产业发展。

1 动物生产行业的应用

1.1 黄粉虫在渔业上的应用

鱼粉(Fish meal, FM)是水产饲料中最重要的组成部分,但随着FM需求不断增加和供给不断减少,水产饲养成本不断上升(Sandra *et al.*, 2020)。世界渔业急需优质替代品替代FM以解决资源紧张的难题。黄粉虫作为价格低廉且富含蛋白质的高性价比昆虫资源自然而然进入了科研人员的视野。

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Piccolo 等 (2017) 将传统商业饲料 (Traditional commercefeed, TCF) 中 25%FM 替换成黄粉虫虫粉 (Yellow mealworm meal, YMM) 饲喂金头鲷 *Sparus aurata* 后提高了饲料转化率和蛋白效率比, 当替换比从 25% 增至 50% 时, 金头鲷营养物质消化率较于前者显著降低。斑鳊 *Siniperca scherzeri* 生长速率和饲料利用率随 FM 对 YMM 替代比提升有上升趋势, 但仅限 20% 以内, 超 20% 后生长速率和饲料利用率下降 (Sankian *et al.*, 2018)。40%FM 被 YMM 替代后的 TCF (60%TCF, 其他比例依此类推) 最有利于锦鲤 *Cyprinus carpio haematopterus* 幼鱼生长 (任顺等, 2020)。用 50%TCF 饲喂窄爪螯虾 *Pontastacus leptodactylus* 后其特定生长速率、蛋白质效率比、蜕皮频率和饲料转化率均有提升, 但存活率降低 (Mazlum *et al.*, 2021)。

鱼虾个体饲喂混有黄粉虫粉的传统商业饲料 (Traditional commercial feed mixed with yellow mealworm meal, TMY) 后个体脂肪、氨基酸等营养物质变化也备受关注。用 75%TCF 饲喂黑斑鲷 *Pagellus bogaraveo*, 发现鱼肉亚油酸含量随 YMM 加入显著提高; 但替换率增至 50% 时, 黑斑鲷动脉粥样硬化值和血栓指标显著升高 (Iaconisi *et al.*, 2017a)。用 TMY 饲喂虹鳟 *Oncorhynchus mykiss* 后虹鳟饱和脂肪酸含量上升而二十碳五烯酸和二十二碳六烯酸等不饱和脂肪酸含量降低, 影响程度与替换比有关 (Iaconisi *et al.*, 2017b)。直接饲喂鲜黄粉虫能提高大鲵 *Andrias davidianus* 肌肉脂肪含量, 但抑制大鲵生长 (冯麒凤等, 2021)。用 TMY 饲喂金头鲷和虹鳟后二者肌肉氨基酸谱发生明显变化 (Iaconisi *et al.*, 2019), 人体必需氨基酸含量变化尤其值得关注。

鱼虾终产量和肉质与其整体健康状况密切相关, 鱼虾饲喂 TMY 后机体免疫力、肠道微生物群及配子质量等生理变化研究也有报道。Henry 等 (2018) 研究发现用 TMY 饲喂欧洲鲈鱼 *Dicentrarchus labrax* 能提高鲈鱼血清溶菌酶活性。Peng 等 (2019) 在 TCF 中添加 4%、8%、12% 和 16% 的 YMM, 发现前 3 种比例能够显著

提高罗氏沼虾 *Macrobrachium rosenbergii* 日生长率及蛋白质效率比, 且所有实验组沼虾体内超氧化物歧化酶、酚氧化酶及溶菌酶活性提高, 表明沼虾在食用 TMY 后免疫力得到强化。用 TMY 饲喂锦鲤后锦鲤血清及肝脏中碱性磷酸酶、酸性磷酸酶和谷丙转氨酶等酶活性与对照相比变化明显, 当替换比在 20% 至 40% 时锦鲤综合生理状况最佳 (任顺等, 2021)。Gelinçek 和 Gunes (2020) 研究发现饲喂 TMY 能够提高黑海鳟鱼 *Salmo trutta labrax* 精子和卵子质量, 从而在繁育中形成更优质个体。Antonopoulou 等 (2019) 认为鱼类肠道微生物菌群健康状况与鱼类生长密切相关, 饲喂 50%TCF 可正向调节金头鲷、欧洲鲈鱼和虹鳟 3 种鱼肠道微生物菌群。此外, TMY 还能增加鲤鱼 *Cyprinus carpio* 长度, 改变鲤鱼肠道微生物群 (Mamuad, 2021)。

值得一提的是, 多项研究都指向一个共同论点, 即 YMM 替代 FM 只在一定比例内起积极作用, 超出一定比例后效益变差, 过高甚至不如 TCF, 且不同物种最适比例不尽相同。这个结论虽然对实际生产有积极意义, 但显然美中不足。Ido 等 (2019) 发现 YMM 用作饲料时, 其脂含量高低对饲养效果影响显著, 脱脂 YMM 完全替代 FM 喂食红海鲷 *Pargus major*, 可显著提高其生长速率, 同时提高其对爱德华氏菌 *Edwardsiella tarda* 抵抗力。利用从 YMM 中提取的昆虫蛋白粉完全替代 FM 喂食虹鳟能提高虹鳟生长性能且无副作用 (Rema *et al.*, 2019; Chemello *et al.*, 2020; Terova *et al.*, 2021)。

1.2 黄粉虫在畜牧业上的应用

自建国以来, 我国畜牧业发展迅猛, 规模和产值不断扩大。但随着自然资源和生物资源不断消耗, 畜牧 TCF 主要成分 (鱼粉、豆粕和肉骨粉等) 生产成本愈发昂贵。在此背景下黄粉虫作为优质昆虫资源, 近年在畜牧养殖方面的研究成果如雨后春笋般不断涌现。

孔春梅等 (2017) 研究表明 TMY 不会引起肉鸡体内氨基脒 (呋喃西林代谢物) 残留, 可安全用于肉鸡养殖。在肉鸡 TCF 中添加 5% 比例

YMM 后发现肉鸡肠道微生物群特征利于肉鸡对饲料消化吸收;但当比例提至 10%和 15%时则对其生长不利(Biasato *et al.*, 2019; Dalmoro *et al.*, 2021)。TCF 中添加 5%YMM 可增加肉鸡体重增长率和饲料转化率;降低血清白蛋白与球蛋白比值并降低肉鸡肠道大肠杆菌含量(Sedgh *et al.*, 2021)。在 TCF 中添加少量 YMM 能够减少肉鸡肠道致病菌丰度(Benzertiha, 2019)。TMY 能改善火鸡肠道菌群并提高机体抗氧化能力(Kozłowski *et al.*, 2021)。TCF 中适当添入 YMM 和小麦胚芽能提高蛋鸡蛋白质和蛋抗氧化能力,且不会影响蛋鸡健康(Stastnik *et al.*, 2021; 郑紫薇等, 2021)。家兔膳食中用黄粉虫虫油替代大豆油后家兔健康状况与对照相比无异,说明黄粉虫虫油是兔饲料合适脂肪来源(Gasco *et al.*, 2019)。通过对关键代谢组织代谢组、转录组、脂质组综合分析, Sandra 等(2020)发现饲喂 TMY 对猪影响较小;另外 Ringseis 等(2021)研究表明饲喂 TMY 既不会引起猪氧化应激反应,也不会激活猪生长关键代谢组织中氧化应激敏感信号通路,因此 YMM 可作为猪饲料来源。饲喂 TMY 有助于提高北非石鸡 *Alectoris barbara* 生重与熟重且鸡肉脂肪酸谱发生明显变化,油酸含量上升而软脂酸含量下降(Secci *et al.*, 2018)。Zahra 等(2020)发现在日本鹌鹑 *Coturnix japonica* TCF 中适当添加 YMM 能促进日本鹌鹑每日进食。

除本身直接加工成饲料外,饲养黄粉虫幼虫(Yellow mealworm, YM)过程中产生的副产品(养殖过程中死亡虫体,黄粉虫虫皮及黄粉虫虫粪等)也能加工后添入饲料。陈耀等(2021)发现在不影响肉鹅生长前提下,在 TCF 中添加虫粪可降低饲料成本,提高经济效益。在海兰褐蛋鸡日粮中添加 4%和 6%黄粉虫副产品能加深鸡蛋色泽,降低蛋黄中胆固醇含量,从而提高蛋的品质(郭志等有等, 2020)。在 TCF 中添加 20%-30%虫粪可提高鹅营养物质消化率(韦毅等, 2021)。

YMM 及其副产品加工后部分替代 TCF 主要成分(鱼粉及豆粕等)能够促进部分物种生长发育以及提高农副产品品质;与鱼虾相比,畜牧

TCF 添加 YMM 后对牲畜产生副作用的报道较少,推测是因为海洋生物和陆地生物对脂肪需求和代谢能力不同。

2 黄粉虫在食品行业上的应用

2.1 食品加工

包括黄粉虫在内的多种昆虫都具有较高食用价值, Son 等(2020)对脱脂 YMM 和虫油的营养价值进行综合评估,认为脱脂 YMM 和虫油可作为出色的食品原料加入食品生产,但人们普遍不愿食用昆虫,这是对昆虫资源的浪费。故改进昆虫食品加工工艺和技术以提升其可食用性一直是个热门话题。De 等(2019)利用工业设备成功制成以 YMM 为原料的黄粉虫面团(Mealworm paste, MP), MP 在低温下短期储存不易变质,且 MP 也被证明适用于发酵。田晶(2020)利用响应面法改进了 YMM 饼干加工工艺,使 YMM 饼干食用效果更佳。

2.2 食品安全

近年也有学者针对 YMM 加工食品的安全性进行评价。Belleggia 等(2020)研究发现即使饲养环境出现较低水平李斯特菌 *Listeria innocua* 污染,李斯特菌也会在黄粉虫肠道中繁殖,进而对食用者健康产生潜在威胁;饲喂昆虫的饲料和产生的虫粪被证明是李斯特菌污染潜在来源。

3 黄粉虫与营养开发

3.1 营养富集

Dong 等(2021)在 TCF 中添加 20 $\mu\text{g/g}$ 亚硒酸钠后饲喂黄粉虫,发现黄粉虫总硒量增加近 83 倍,其中有机型占 97%以上;富硒 YMM 可能具有更广泛的应用价值,因为它们可作为人类膳食硒补充剂来源,或是作为饲料用于生产富硒的肉蛋奶产品。

3.2 黄粉虫营养学动态评估

在黄粉虫大规模饲养中往往以黄粉虫达到终龄为最佳收获时间,但有研究者发现不管从经

济或是营养角度考虑,终龄幼虫都不是最佳收获点。Yu 等(2021)研究发现黄粉虫不同营养成分(氨基酸和脂肪酸等)比例会随着发育而不断改变,同时考虑到黄粉虫发育后期饲料转化率降低的因素,收获时中间龄期幼虫将是比终龄幼虫更佳的选择。这一发现对黄粉虫规模化生产意义重大,有望在增加经济效益的同时提升其营养价值。

4 黄粉虫与环境保护

4.1 塑料生物降解

Brandon 等(2021)发现黄粉虫肠道微生物群产生的分泌物和黄粉虫自身产生的乳化因子能有效介导塑料生物降解,对黄粉虫肠道微生物群产生的分泌物及其自身产生的乳化因子进行富集后对塑料降解效率更高;研究发现了 8 种与聚苯乙烯(Polystyrene, PS)降解有关的黄粉虫肠道微生物。利用黄粉虫对 PS 和低密度聚乙烯(Low-density polyethylene, LDPE) 2 类塑料进行生物降解,黄粉虫表现出塑料降解的广泛性和局限性;PS 经黄粉虫生物降解后重均分子量(M_w)和数均分子量(M_n)均下降,体现出黄粉虫生物降解塑料的广泛性;而针对两种聚乙烯材料(LDPE1 和 LDPE2),黄粉虫则表现出两种不同解聚模式,即平均分子量较低的 LDPE1 经黄粉虫降解后 M_w 和 M_n 均下降,相对分子量较高的 LDPE2 经黄粉虫降解后 M_w 下降但 M_n 上升,体现出黄粉虫生物降解塑料的局限性。另外,黄粉虫肠道微生物群在降解塑料过程中虽发挥重要作用,但并非所有类型塑料生物降解都依赖肠道微生物群,例如 LDPE 在塑料降解过程中对肠道微生物依赖性较弱(Yang *et al.*, 2021)。M 能降解聚氯乙烯(Polyvinyl chloride, PVC)和聚乳酸(Polylactic acid, PLA),但降解不完全(Peng *et al.*, 2020; Peng *et al.*, 2021)。多项研究都指出黄粉虫取食塑料后肠道微生物群组成和微生物聚集出现显著变化(Peng *et al.*, 2020, 2021; Brandon *et al.*, 2021)。

4.2 农业废弃物与城市污染生物降解

传统农业废弃物和城市污水污泥的绿色处

理一直是个难题。Yang 等(2019)发现黄粉虫对麦秆(WS)、稻秆(RS)和米糠(RB)具有 90%以上消耗利用率。李双喜等(2017)将麦麸和城市污泥以 1:1 配比制成饲料饲喂黄粉虫,黄粉虫生长快且死亡率低。熊晓莉等(2016)研究表明 $Fe(SO_4)_3$ 和黄粉虫壳聚糖适当比例复配后能有效净化养殖废水。

4.3 吸附重金属

Yang 等(2019)发现黄粉虫取食 RS、WS 和 RB 后产生的虫粪在高温下制成的生物炭能吸附各类重金属,且取食 RS 后产生的虫粪在 600 °C 下制成的生物炭对 Pb(II)、Cd(II)、Cu(II)、Zn(II)以及 Cr(VI)具有最佳吸附性能。

5 农业生产方面的应用

目前黄粉虫在农业生产方面研究报道较少,未来研究空间较大。Przemieniecki 等(2021)发现 YMM 矿物肥料能刺激芽孢杆菌 *Bacillus* 生长同时抑制镰刀菌 *Fusarium* 繁殖,增强土壤养分,防止幼苗衰退,促进小麦幼苗健康生长。在土壤中添加一定比例黄粉虫粪能促进牵牛花 *Pharbitis nil*、百日草 *Zinnia elegans*、波斯菊 *Cosmos bipinnata*、杜鹃花 *Rhododendron simsii* 和月季花 *Rosa chinensis* 的生长发育,但不同花卉作物适宜添加比不同(贾红, 2018)。YMM 肥料针对其他作物的综合适用性有待进一步研究。

6 展望

黄粉虫作为优质昆虫资源在国内外有着巨大的研究和应用市场,虽近年研究进展不断,但距真正实现黄粉虫高效综合利用还有不小距离。渔业上虽然脱脂 YMM 完全替代 FM 已经有了理论上的可能,但是目前关于饲喂脱脂 YMM 对鱼类生长影响的研究较少,同时副产品虫油的再利用也需关注。黄粉虫虽能有效降解塑料等环境污染物,但降解程度有限;且各项研究表明这些污染物不利于黄粉虫的生长发育,黄粉虫往往难以正常完成其生命周期。另外取食塑料后黄粉虫的

营养价值和细胞毒性发生变化,已不可用于饲料生产或是食品加工,故目前还难以实现变废为宝的绿色循环生产。黄粉虫作为动物饲料的研究层出不穷,但在植物化肥方面的研究极少,其在农业生产方面的应用可以作为未来的研究侧重点。

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