

聚乙烯微塑料对蠋蝽生长发育及捕食的不利影响*

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摘 要 【目的】初步探讨日益增多的微塑料对天敌蠋蝽 *Arma chinensis* 生长发育和捕食能力的影响, 为未来探究微塑料在陆地昆虫食物链中的迁移和转化提供参考。【方法】将聚乙烯微塑料 (Polyethylene microplastics, PE-MPs) 加入黄粉虫 *Tenebrio molitor* 幼虫饲料中, 通过黄粉虫幼虫饲养蠋蝽, 对黄粉虫幼虫的存活率和体重, 蠋蝽生长发育和捕食能力进行评估。【结果】黄粉虫幼虫取食了含有 PE-MPs 的饲料后, 存活率和体重显著下降 ($P < 0.05$)。虽然 PE-MPs 的介入缩短了蠋蝽若虫的发育历期, 增加了蠋蝽成虫的体重, 但使蠋蝽的死亡率显著增加 ($P < 0.05$), 延长了蠋蝽成虫的捕食时间。同时, 在黄粉虫和蠋蝽肠道分别检测到了 PE-MPs 的存在, 说明微塑料会在食物链中进行传递。【结论】当聚乙烯微塑料加入黄粉虫幼虫饲料之后, 不仅对黄粉虫幼虫造成不利影响, 这种不利影响也会传递至蠋蝽体内, 对蠋蝽的存活和捕食造成威胁。

关键词 蠋蝽; 聚乙烯; 微塑料; 天敌昆虫; 食物链; 生长发育

Adverse effects of polyethylene microplastics on the growth, development and predation of *Arma chinensis*

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Abstract [Aim] To investigate the impact of ingesting microplastics on the growth, development, and predatory capabilities of *Arma chinensis*. In addition, this paper aims to provide valuable insights on microplastic migration and transformation within the terrestrial insect food chain. [Methods] Polyethylene microplastics (PE-MPs) were incorporated into the diet of *Tenebrio molitor* larvae, which were subsequently fed to *A. chinensis*. The survival rate and body weight of *T. molitor* larvae, the growth and development of *A. chinensis*, and the predatory ability of *A. chinensis*, were assessed. [Results] Consumption of PE-MPs caused a significant decrease in both the survival and body weight of *T. molitor* larvae ($P < 0.05$). Consuming *T. molitor* larvae that had consumed PE-MPs also shortened the developmental duration of *A. chinensis* nymphs, increased the body weight of *A. chinensis* adults, and increased the mortality rates of both nymphs and adults. It also reduced the predatory ability of *A. chinensis* adults ($P < 0.05$). Polyethylene microplastics were detected in the intestinal tracts of both *T. molitor* larvae and *A. chinensis*, indicating that these were probably transferred to the latter through the food chain. [Conclusion] The incorporation of PE-MPs in the diet of *T. molitor* larvae not only had a detrimental impact on their survival, but also resulted in the transmission of PE-MPs to *A. chinensis*, which also reduced the survival and predatory

*资助项目 Supported projects: 国家重点研发计划项目 (2021YFD1400200); 新疆维吾尔自治区天山英才计划资助 (2021282); 新疆农业大学研究生科研创新项目 (XJAU2024035)

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收稿日期 Received: 2024-04-24; 接受日期 Accepted: 2024-09-19

capability of this species.

Key words *Arma chinensis*; polyethylene; microplastics; natural enemy insect; food chain; growth and development

随着世界人口的稳步上升, 粮食需求日益增长, 塑料大棚、农业地膜覆盖和塑料滴灌带灌溉已然成为普遍的农业栽培种植技术 (Bayramov and Gasanov, 2021; An *et al.*, 2022)。聚乙烯 (Polyethylene, PE) 作为世界上产量最高、种类最多的合成树脂之一, 大量用于农业生产中, 直接导致了废弃塑料的大量积累。塑料通过破碎和降解会形成微塑料 (Microplastics, MPs), 微塑料的质量轻, 粒径小, 迁移范围广, 造成的危害严重 (Thompson *et al.*, 2004), 因而需要我们更多的关注。聚乙烯微塑料 (Polyethylene microplastics, PE-MPs) 会通过多种途径进入农田生态系统, 主要包括农用地膜残留、其他塑料制品、有机肥及灌溉用水的使用等 (Bläsing and Amelung, 2018; Kleunen *et al.*, 2020; Liu *et al.*, 2020; 李鹏飞等, 2021; 杨光蓉等, 2021; 杨杰等, 2021)。Ren 等 (2024) 研究表明, 我国农田中大塑料的平均残留量和微塑料的平均丰度分别为 103 kg/hm² 和 4 537 items/kg (土壤干重)。

微塑料不仅会影响作物的萌发和生长发育 (Weithmann *et al.*, 2018; Bosker *et al.*, 2019; Machado *et al.*, 2019), 还会通过根部对养分和水分的吸收进入茎和叶等部位 (李连祯等, 2019; Zhang *et al.*, 2023), 微塑料被植物吸收后, 还可能通过其他生物的摄食行为进行转运, 通过食物链沿营养级逐级积累, 对农业生产和人类健康构成潜在安全风险 (骆永明等, 2018; 周雨苗等, 2021)。研究表明, 微塑料可以在生物体内及生物之间发生迁移、转运, 并在生物体内累积, 产生生态学效应 (Cauwenberghe *et al.*, 2015; Abbasi *et al.*, 2018; Li *et al.*, 2024)。昆虫是自然界中种类最丰富、生物量最大的生物类群, 也是关键生态系统服务的主要提供者, 可以为其他生物提供食物、授粉、分解、控制害虫等多种服务, 在生态系统中有着至关重要的作用 (Holden, 2006; Zappalà *et al.*, 2013; Biondi *et al.*, 2018)。但微塑料的存在会对昆虫的生存、繁殖、发育和肠道微生物群产生负面影响 (Andrea and Grecia, 2023;

Shen *et al.*, 2023)。

蠋蝽 *Arma chinensis* 作为农林业上一种重要的捕食性天敌昆虫, 可以捕食鳞翅目、鞘翅目、膜翅目及半翅目等多种害虫, 能够很好的维持农田生态系统的稳定 (潘明真等, 2018; Zhao *et al.*, 2018)。为探究微塑料是否会在食物链中对各营养级造成影响, 同时也为了探明日益增多的微塑料对蠋蝽的生长发育及捕食能力的影响, 本研究选择含有大量蛋白质、高度不饱和脂肪酸以及维生素和矿物质, 且氨基酸组成均衡 (Ravzanaadii *et al.*, 2012) 的黄粉虫 *Tenebrio molitor* 幼虫作为第二营养级, 使用拌有 PE-MPs 的麦麸 (第一营养级) 进行饲养。饲养 15 d 后, 使用黄粉虫幼虫饲喂蠋蝽 (第三营养级), 观察蠋蝽若虫的生长发育和存活情况。马铃薯甲虫 *Leptinotarsa decemlineata* 是世界范围马铃薯上极具毁灭性的检疫性有害生物, 也是我国重要的农业植物检疫性害虫 (Liao *et al.*, 2021; Liu *et al.*, 2023), 本研究使用马铃薯甲虫测定蠋蝽成虫的捕食能力。

本研究评估了 PE-MPs 对黄粉虫幼虫存活率和体重、蠋蝽生长发育、成虫体重和捕食能力的影响, 为未来探究微塑料在陆地昆虫食物链中的迁移和转化提供了基础信息。

1 材料与方法

1.1 供试昆虫

黄粉虫幼虫由新疆农业大学昆虫生态实验室提供, 初始龄期为 5 龄。蠋蝽成虫购自河南省济源白云实业有限公司, 在新疆农业大学昆虫生态实验室饲养, 仅使用麦麸饲养的黄粉虫幼虫进行饲养, 每个养虫皿中释放 4 头蠋蝽成虫 (2♀ + 2♂), 置于智能人工培养箱内 (RXM-258A, 宁波江南仪器厂), 饲养温度为 (27±1) °C、相对湿度 70%±5%、光周期 16 L : 8 D, 饲养至第 3 代 2 龄若虫后开始试验。马铃薯甲虫成虫采自新疆维吾尔自治区昌吉回族自治州阜康市柳城子西村马铃薯田 (44.177 452°N, 87.921 291°E),

采集后放置在人工气候箱内饲养,饲养条件:环境温度(27 ± 1) $^{\circ}\text{C}$,相对湿度 $70\%\pm 5\%$,光周期 $16\text{ L}:8\text{ D}$ 。每个器皿中放入4头马铃薯甲虫成虫,每天更换新鲜的马铃薯叶片,确保开始实验时马铃薯甲虫有较好的活力状态。

1.2 PE-MPs 对黄粉虫幼虫的影响

试验所用 PE-MPs 购自广东省东莞市特塑朗化工原料厂,粒径为 $1-1100\text{ }\mu\text{m}$,粒度分布的平均值约为 $500\text{ }\mu\text{m}$,纯度 $\geq 99.99\%$ 。

随机挑选体长在 1.5 cm 左右、形态大小均匀的黄粉虫幼虫50头(龄期为5龄),置于 12 cm 塑料碗中,在恒温(25 ± 1) $^{\circ}\text{C}$,相对湿度 $70\%\pm 5\%$,遮光条件下培养。试验开始前,先用麦麸饲养3d,之后换上新的塑料碗。处理组用 PE-MPs 和麦麸按质量比为 $1:5$ 进行混合作为唯一食物,对照组用麦麸作为唯一食物,每组重复3次。每天及时清理死亡的黄粉虫幼虫,每4d记录一次存活黄粉虫幼虫数量,并随机称量15头黄粉虫幼虫净重,连续记录32d。32d后,取黄粉虫肠道置于生物显微镜(型号:Panthera L.)下观察 PE-MPs 颗粒的摄入情况。

1.3 取食 PE-MPs 后黄粉虫幼虫对蠋蟥的影响

试验开始前,使用 PE-MPs 和麦麸质量比为 $1:5$ 的混合物饲养黄粉虫幼虫15d。试验组使用处理后的黄粉虫幼虫饲养蠋蟥,每组放入约30头蠋蟥2龄若虫,设置6个重复。对照组使用麦麸饲养的黄粉虫幼虫进行饲养,每组放入约30头蠋蟥2龄若虫,设置4个重复。每日记录蠋蟥各龄期的存活数量、死亡数量、取食量及发育时间。

蠋蟥饲养至成虫后,将成虫和若虫分开饲养,从蠋蟥变为成虫开始,统计3d内蠋蟥成虫的死亡数量,记录3龄蠋蟥成虫的体重(雌雄分开称重)。取3龄蠋蟥成虫肠道置于生物显微镜(型号:Panthera L.)下观察 PE-MPs 颗粒的摄入情况。使用3龄蠋蟥成虫进行捕食能力测试,处理组和对照组各设置15个重复,分别放入4头马铃薯甲虫成虫和1头生长状况良好的蠋蟥成虫,统计捕食4头马铃薯甲虫所需时间,

蠋蟥死亡后舍弃该组数据,最后统计到对照组有效数据14组,PE-MPs 处理组有效数据10组。

1.4 数据分析

试验数据采用 Excel 2021 进行统计整理,利用 SPSS 26.0 统计软件进行数据分析,经正态性和方差齐性检验后,对黄粉虫幼虫体重及存活率、蠋蟥若虫发育历期及存活率、3龄成虫体重和捕食能力进行单因素方差分析,利用 Duncan 氏新复极差法进行差异显著性检验,比较不同处理黄粉虫幼虫体重和存活率的差异显著性、蠋蟥若虫发育历期和存活率及3龄成虫体重和捕食能力的差异显著性。结果利用 GraphPad Prism 10.0 进行作图。

2 结果与分析

2.1 PE-MPs 对黄粉虫的影响

取食 PE-MPs 会降低黄粉虫幼虫单体重及存活率。取食 PE-MPs 后的前12d,黄粉虫幼虫单体重有所增加,12d之后,处理组的黄粉虫重量逐渐下降,对照组的黄粉虫幼虫单体重一直稳步上升(图1:A)。从存活率看,12d之后处理组与对照组之间的存活率有显著性差异(12、20和24d: $df=1$, $F=25.000$, $P=0.007$; 16d: $df=1$, $F=169.000$, $P<0.001$; 28d: $df=1$, $F=36.571$, $P=0.004$; 32d: $df=1$, $F=87.000$, $P=0.001$)(图1:B)。通过生物显微镜观察发现,PE-MPs 颗粒通过黄粉虫幼虫的取食进入了黄粉虫幼虫肠道内(图2)。

2.2 PE-MPs 对蠋蟥生长发育及捕食的影响

PE-MPs 能够显著提高蠋蟥成虫的体重,缩短蠋蟥若虫的发育历期(图3:A,B)。取食以 PE-MPs 饲喂的黄粉虫幼虫,3龄蠋蟥成虫体重显著提高(雄成虫: $df=1$, $F=50.959$, $P<0.001$; 雌成虫: $df=1$, $F=61.976$, $P<0.001$),雄成虫平均重量为 0.0566 g ,比对照组雄成虫重 0.0088 g ,雌成虫平均重量为 0.0783 g ,比对照组雌成虫重 0.0140 g (图3:A);2龄若虫的发育时间显著缩短($df=1$, $F=8.914$, $P=0.017$),而

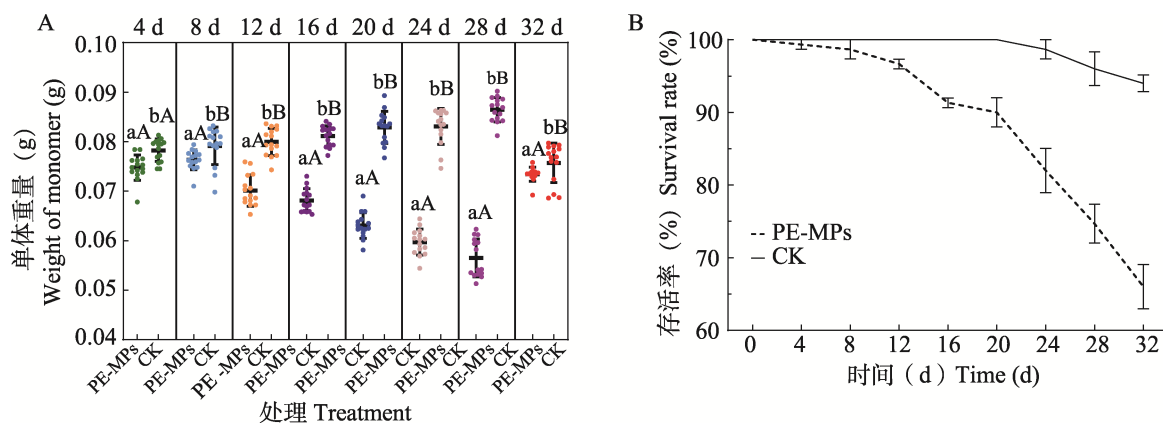


图 1 聚乙烯微塑料 (PE-MPs) 对黄粉虫幼虫体重 (A) 和存活率 (B) 的影响
 Fig. 1 The impact of polyethylene microplastics (PE-MPs) on the body weight (A) and survival rate (B) of *Tenebrio molitor* larvae

PE-MPs: 聚乙烯微塑料; CK: 仅使用麦麸进行饲养, 下图及下表同。图中数据为平均值 $\pm$ 标准误, 不同小写字母表示在 0.05 水平上差异显著, 不同大写字母表示在 0.01 水平上差异显著 (Duncan 氏新复极差法检验)。图 3 和图 5 同。
 PE-MPs: Polyethylene microplastics; CK: Only wheat bran was used for feeding, the same below. Data in figure are mean $\pm$ SE, Different lowercase letters indicate significant difference at the 0.05 level, and different capital letters indicate significant difference at the 0.01 level by Duncan's multiple range test. The same for Fig. 3 and Fig. 5.

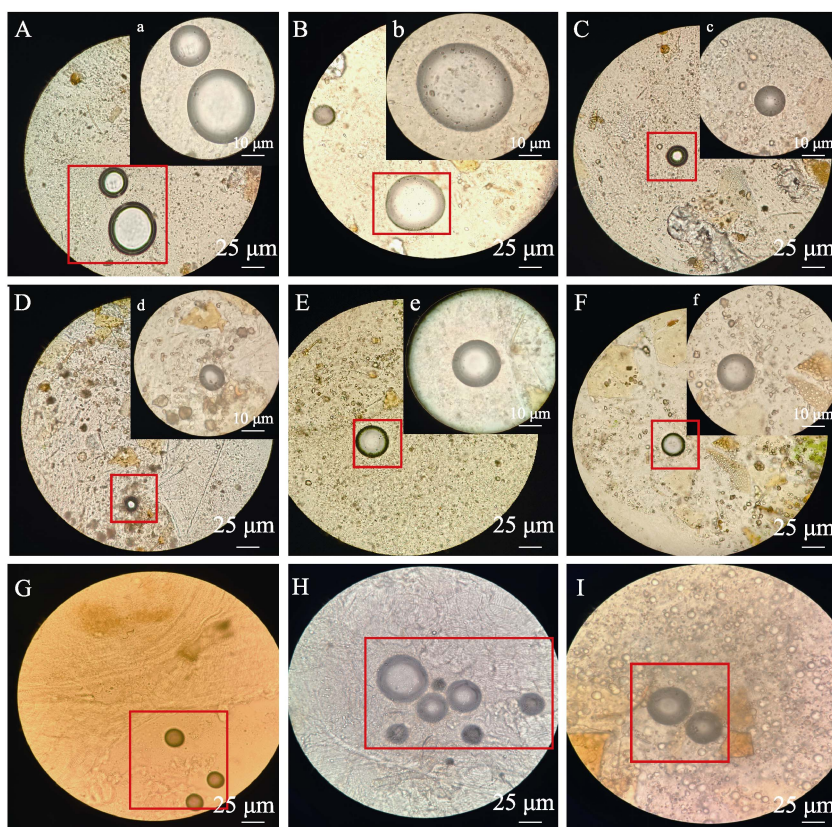


图 2 黄粉虫幼虫肠道中的聚乙烯微塑料
 Fig. 2 Polyethylene microplastics in the intestinal tract of *Tenebrio molitor* larvae

A-I. 黄粉虫幼虫肠道内的聚乙烯微塑料颗粒, 放大倍数为: 目镜 $\times$ 物镜=10 $\times$ 40;

a-f. A-F 图的放大图, 放大倍数为: 目镜 $\times$ 物镜=10 $\times$ 100。

A-I. Polyethylene microplastic particles in the intestinal tract of *T. molitor* larvae, Magnification: Eyepiece $\times$ objective = 10 $\times$ 40; a-f. Magnification of A-F, Magnification: Eyepiece $\times$ objective = 10 $\times$ 100.

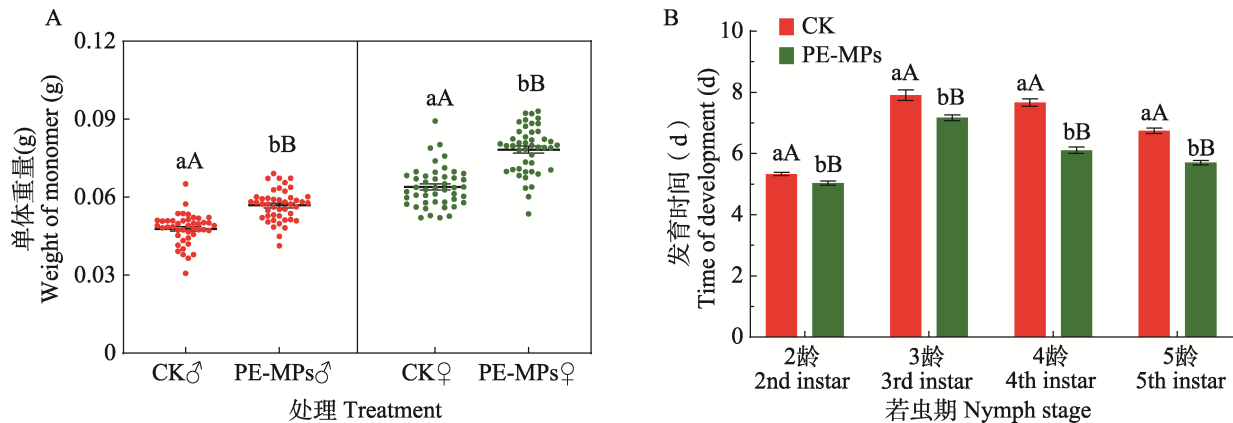


图3 聚乙烯微塑料对蠋蚣成虫体重 (A) 和若虫发育时间 (B) 的影响

Fig. 3 The impact of polyethylene microplastics on the body weight of *Arma chinensis* adult (A) and the duration of nymph development (B)

3 龄 ($df=1$, $F=16.682$, $P=0.004$)、4 龄 ($df=1$, $F=95.940$, $P<0.001$) 和 5 龄 ($df=1$, $F=77.391$, $P<0.001$) 蠋蚣若虫相对于对照组, 发育时间缩短极显著 (图 3: B), 处理组蠋蚣 2-5 龄的平均发育时间缩短了 3.635 d。此外, 通过统计蠋蚣若虫的取适量, 发现处理组的蠋蚣若虫取食量大于对照组 (图 4)。

取食以 PE-MPs 饲喂的黄粉虫幼虫显著降低了蠋蚣若虫的存活率 (表 1)。处理组 2 龄 ($df=1$, $F=1.973$, $P=0.198$) 和 5 龄 ($df=1$, $F=0.004$, $P=0.951$) 蠋蚣的存活率与对照无显著差异, 而 3 龄 ($df=1$, $F=7.260$, $P=0.027$)、4 龄 ($df=1$, $F=13.698$, $P=0.006$) 若虫, 及整个若虫期 ($df=1$, $F=72.962$, $P<0.001$) 存活率均受到 PE-MPs 的显著影响。PE-MPs 处理下, 3 龄蠋蚣存活率比对照低 9.03%, 4 龄存活率比对照低 13.67%,

整个若虫期的存活率仅为 49.21%, 比对照低 20.33%。

使用饲喂 PE-MPs 的黄粉虫幼虫饲养蠋蚣, 3 日龄成虫的死亡率比对照组高 42.5%, 差异极显著 ($df=1$, $F=39.634$, $P<0.001$) (图 5: A)。

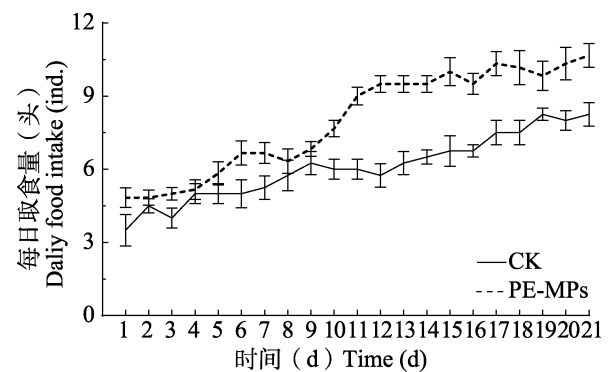


图4 蠋蚣若虫每日取食量

Fig. 4 Daily food intake of *Arma chinensis* nymphs

表 1 不同处理下蠋蚣若虫的存活率

Table 1 Survival of *Arma chinensis* nymphs under different treatments

处理 Treatment	若虫存活率 (%) Nymphal survival rate (%)				
	2 龄 2nd instar	3 龄 3rd instar	4 龄 4th instar	5 龄 5th instar	2-5 龄 2nd-5th instar
对照 CK	93.99±2.93 aA	84.33±3.39 aA	91.02±3.54 aA	96.50±2.10 aA	69.54±2.17 aA
聚乙烯微塑料 Polyethylene microplastics	89.51±1.75 aA	75.30±1.61 aB	77.35±1.93 bB	96.70±2.11 aA	49.21±1.32 bB

表中数据为平均值±标准误, 同列不同小写字母表示在 0.05 水平上差异显著, 不同大写字母表示在 0.01 水平上差异显著 (Duncan 氏新复极差法)。

Data in the table are mean ± SE. Different lowercase letters in the same column indicate significant difference at the 0.05 level, and different capital letters indicate significant difference at the 0.01 level (Duncan's new multiple range test).

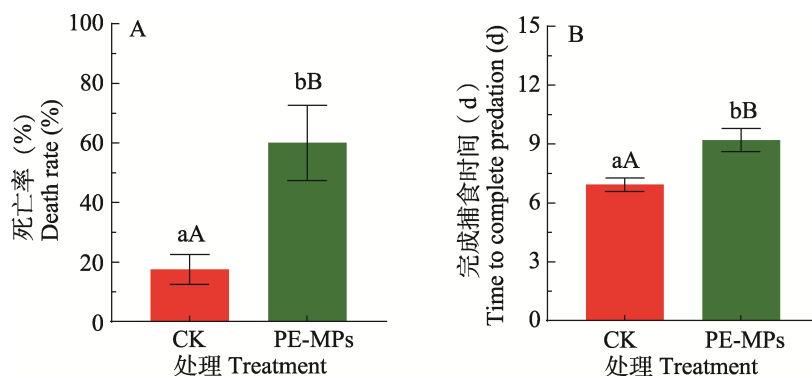


图5 聚乙烯微塑料对蠋蝽成虫死亡率 (A) 和捕食能力 (B) 的影响
Fig. 5 The impact of polyethylene microplastics on the death rate (A) and predation efficacy (B) of *Arma chinensis* adult

处理组平均捕食时间为 9.20 d, 比对照组长 2.27 d ($df = 1, F = 12.605, P = 0.002$), 处理组蠋蝽成虫捕食完 4 头马铃薯甲虫成虫的捕食时间最长可达 12 d, 对照组成虫最长捕食完成时间为 9 d (图 5: B)。通过生物显微镜观察发现, PE-MPs 颗粒随蠋蝽的取食进入了蠋蝽的肠道内(图 6: A-F)。

3 讨论

黄粉虫是一种可持续、安全和营养丰富的新

型饲料原料, 具有繁殖快、蛋白含量高、氨基酸组成合理、适口性好、几丁质和抗菌肽等生物活性成分含量高等优点 (Kumar *et al.*, 2019; 林声雄等, 2023; 宋柏辰等, 2023)。本研究发现饲喂 PE-MPs 的黄粉虫幼虫存活率和体重均明显下降, 这与李鹏浩等 (2023)、张诗焱等 (2023) 等研究聚苯乙烯对黄粉虫幼虫的影响结果一致。这是因为将 PE-MPs 加入黄粉虫幼虫饲料之后, 黄粉虫幼虫生长发育所需的常规营养减少, 陈耀

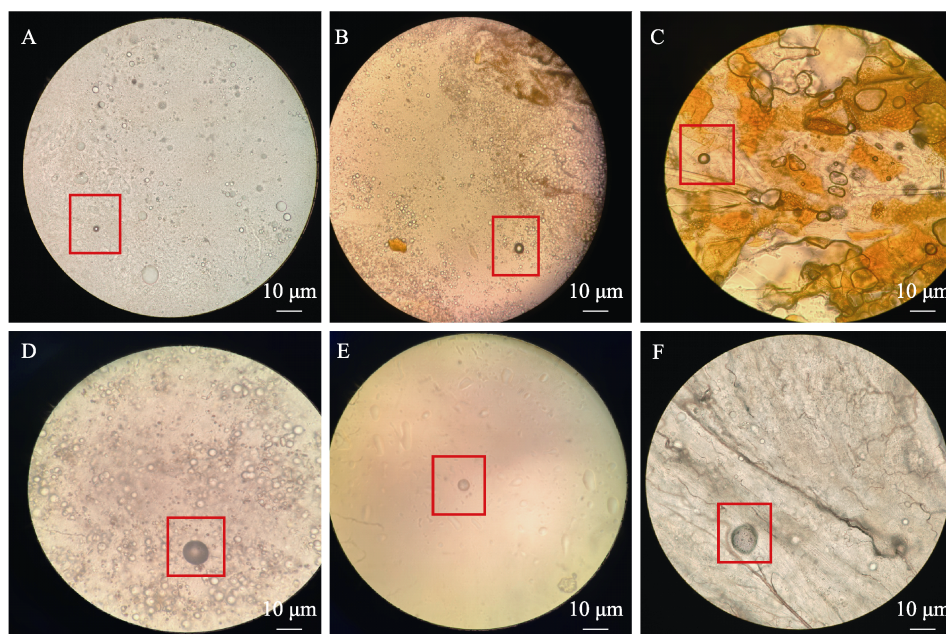


图6 蠋蝽成虫肠道中的聚乙烯微塑料
Fig. 6 Polyethylene microplastics in the intestinal tract of adult *Arma chinensis*

A-F. 蠋蝽成虫肠道内的聚乙烯微塑料颗粒, 放大倍数为: 目镜×物镜=10×100。

A-F. Polyethylene microplastic particles in the intestinal tract of adult *A. chinensis*.

Magnification: Eyepiece × objective = 10×100.

等 (2021) 也论证了这一观点, 黄粉虫幼虫的生长性能随着饲料中聚苯乙烯含量增多而降低。使用 PE-MPs 和麦麸混合物饲养后, 黄粉虫体重显著下降, 这可能是因为黄粉虫摄入的营养物质不足。微塑料对黄粉虫有一定的生物毒性 (李鹏浩等, 2023), 也可能是导致黄粉虫幼虫存活率降低的原因。

食物的适合度 (适口性和营养成分) 直接影响天敌昆虫的取食行为和生长发育 (Zhang *et al.*, 2012; Tang *et al.*, 2013)。本研究发现, 处理组的蠋蝽若虫取食量大于对照组, 这可能是因为微塑料的介入可能使黄粉虫幼虫的适合度发生了改变, 使蠋蝽若虫更喜欢取食。取食饲喂 PE-MPs 的黄粉虫幼虫后, 蠋蝽若虫发育时间缩短, 成虫体重增加。Muhammad 等 (2021) 发现, PS-MPs/NPs 对桑蚕 *Bombyx mori* 有生态毒性, 导致桑蚕死亡。在本研究中, 取食以 PE-MPs 饲养的黄粉虫幼虫, 蠋蝽若虫和成虫的死亡率都显著高于对照组, 这可能是因为 PE-MPs 对蠋蝽有生态毒性, 并且取食 PE-MPs 可能使生物体变得脆弱或降低对病原体感染和生态毒物的抵抗力。Serita 等 (2022) 发现短翅灶蟋 *Gryllobates sigillatus* 摄入微塑料纤维后生长发育受到了显著的负面影响, Silva 等 (2021) 研究发现摄入 PE-MPs 后的摇蚊幼虫 *Chironomus riparius* 引发了免疫反应, 这些研究也有力的支撑了本研究结论。

在进行蠋蝽成虫捕食能力测试时, 处理组有效数据减少, 这可能因为蠋蝽受到 PE-MPs 的影响, 导致死亡。处理组蠋蝽捕食能力显著降低, 可能是 PE-MPs 的介入使蠋蝽成虫的虫体机能下降, 捕食能力降低。在微纳米塑料环境中的鱼类游泳速度变慢, 游泳范围、距离变小以及停止进食 (Cedervall *et al.*, 2012; Mattsson *et al.*, 2015; Choi *et al.*, 2018), 说明微纳米塑料会对动物的行为和身体机能产生影响, 有效的证明了本研究的结果。Murray 和 Cowie (2011) 通过给龙虾喂食带有聚丙烯纤维的鱼, 证明了微塑料可以沿食物链从食物转移到捕食者; Farrell 和 Nelson (2013) 记录了聚苯乙烯微球从蓝贻贝转移到青蟹的过程; Setälä 等 (2014) 的研究也显示塑料

在浮游动物食物网中的营养转移。本研究同样发现, 黄粉虫幼虫和蠋蝽成虫肠道均有 PE-MPs 颗粒积累, 表明 PE-MPs 可以通过食物链进行传递。

PE-MPs 会对黄粉虫幼虫的存活率及体重产生负面作用, 同时, PE-MPs 的介入缩短了蠋蝽若虫的发育历期, 提高了若虫取食量, 增加了蠋蝽成虫的体重, 但使蠋蝽 3 龄、4 龄若虫以及成虫的死亡率显著增加, 降低了蠋蝽成虫的捕食能力, 不利于蠋蝽的生长发育。本研究以黄粉虫幼虫和蠋蝽为研究对象, 发现 PE-MPs 的存在会影响天敌的存活和虫体机能, 这可能会对昆虫食物链造成不利影响, 打破农田生态系统中的动态平衡。本研究探明了微塑料会对食物链中不同营养级的昆虫产生不利影响, 为未来探究微塑料在陆地昆虫食物链中的迁移和转化提供了新的方向。

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