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Ability of Black Soldier Fly (Diptera: Stratiomyidae) Larvae to Recycle Food Waste

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ABSTRACT Accumulation of organic wastes, especially in livestock facilities, can be a potential pollution issue. The black soldier fly, *Hermetia illucens* L. (Diptera: Stratiomyidae), can consume a wide range of organic material and has the potential to be used in waste management. In addition, the prepupae stage of this insect can be harvested and used as a valuable nutritious feed for animal livestock. Five waste types with a wide range of organic source matter were specifically chosen to evaluate the consumption and reduction ability of black soldier fly larvae. *H. illucens* was able to reduce all waste types examined: 1) control poultry feed, 2) pig liver, 3) pig manure, 4) kitchen waste, 5) fruits and vegetables, and 6) rendered fish. Kitchen waste had the greatest mean rate of reduction (consumption by black soldier fly) per day and produced the longest and heaviest black soldier flies. Larvae reared on liver, manure, fruits and vegetables, and fish were approximately the same length and weight as larvae fed the control feed, although some diets produced larvae with a higher nutritional content. The black soldier fly has the ability to consume and reduce organic waste and be utilized as valuable animal feed. Exploration of the potential use of black soldier flies as an agent for waste management on a large-scale system should continue.

KEY WORDS *Hermetia illucens*, waste management, recycling, waste reduction, sustainable agriculture

Introduction

Today, countries are producing more waste with fewer options for its disposal. In 2002, Canada produced 30.4 million tons of solid waste, and the most common method of their disposal was landfills (Cameron et al. 2005). Household waste accounts for 39% (12 million tons in 2002) of all wastes produced, which is composed of 40 and 26% organic and paper goods, respectively. Landfills create leachate and landfill gases, produce unpleasant odors, and attract pests (Cameron et al. 2005). Landfills also are reaching capacity and closing, reducing the available space for future waste and necessitating the creation of new sites. It was reported in 2000 that only 70% of the remaining landfills had a life expectancy of >10 yr (Cameron et al. 2005). Sustainable methods for waste recycling could reduce the burden on landfills and result in the production of valued materials such as compost and animal feed. The black soldier fly, *Hermetia illucens* L. (Diptera: Stratiomyidae), could provide one of these methods.

The black soldier fly is large (13–20 mm) with larvae that can consume a wide range of organic material, ranging from fruits and vegetables to animal remains and manure (James 1935, May 1961). This fly species occurs naturally in confined animal facilities where manure accumulates (Tingle et al. 1975). Because adult black soldier flies do not eat, the larvae must accumulate a large fat body for larval development and adult survival. During the larval stages, black soldier flies can reduce manure waste by 50% (Sheppard et al. 1994). Unlike many pests that consume waste, black soldier fly larvae do not carry bacteria or diseases and are capable of inactivating *Escherichia coli* and *Salmonella* (Erickson et al. 2004). As previously stated, adult black soldier flies do not require additional nutrition for survival (Tomberlin et al. 2002). In addition, adult soldier flies are not considered pests as they do not enter houses and have a short life span (Tomberlin et al. 2002).

Black soldier prepupae are a value-added feed for livestock. The larvae have ∼45.2% crude protein and 31.4% fat, which gives black soldier fly prepupae an estimated value of US$330 per ton when used as feed (Hale 1973, Newton et al. 2005). Studies have shown that black soldier fly prepupae are an acceptable meal replacement for animals such as cockerels, pigs, catfish, and tilapia (Newton et al. 1977, Bondari and Sheppard 1981). Poultry house with 100,000 hens can produce 52.8 tons of prepupae in as little as 8 mo (Sheppard et al. 1994).

We examined the impact of larval diet on the black soldier fly larval development. We predicted that black soldier fly larvae would be able to reduce (consume) all six types of organic waste diets tested: 1) standard

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poultry feed, 2) pig liver, 3) pig manure, 4) kitchen waste, 5) fruits and vegetables, and 6) fish rendering. In addition, it was predicted that black soldier fly larvae would consume more waste that was higher in fat content, as they require a large fat body for development and maintenance of adult survival.

Materials and Methods

The experimental methods used in this study are described in Nguyen et al. (2013). To quickly summarize, diets were chosen to give a wide range of organic waste, ranging from an all-meat to an all-vegetable diet: 1) control poultry feed, 2) pig liver, 3) pig manure, 4) kitchen waste, 5) fruits and vegetables, and 6) fish rendering. Pig manure was gathered from a pig farm in Ridgetown, ON, Canada. Kitchen waste contains both animal and plant matter, ranging from hamburgers to salads, and was obtained from restaurants. Fruits and vegetables were donated by grocery stores. Kitchen waste and fruits and vegetables were obtained from Windsor, ON, Canada. Fish renderings were donated by a fishery in Kingsville, ON, Canada. To keep the diets consistent, a homogenous diet mixture was made by grinding large quantities of each waste type. Waste diets were then packaged and frozen for use throughout the experiment (Nguyen et al. 2013).

Briefly, 150 4-d-old larvae were placed in a separate 30 by 30 by 6.5 cm container with 6 g of waste for each waste type. Daily, larvae were removed, the remaining waste diet was weighed and recorded, and a new 6 g amount of waste diet was given. These larvae were labeled as "handled" larvae because they were disturbed and handled daily. When the daily reduction in provided diet reached 25% in wet weight, the daily amount of diet provided to the larvae was increased by 5 g. The experiment ceased when 40% of "handled" larvae reached the wandering stage.

Nguyen et al. (2013) demonstrated that there is an effect on larval development when handled daily to the extent mentioned above. Therefore, to simulate a more natural environment, a second set of unhandled control replicates were set up and allowed to develop concurrently with handled treatments. These larvae were labeled "unhandled" larvae. Fresh diet was added at the same rate as the handled treatments. When 40% of the larvae in the previous "handled" treatment reached the wandering stage, mortality, weight, and length also were measured for the "unhandled" larvae. Ten samples of three larvae per sample from each experimental container were used to measure larval weight owing to the sensitivity of the available scale. A sample of 10 larvae from each experimental container was used to record the length, taken as the longest measure when crawling.

A third set of control replicates was set up at the same time as described above, but contained no larvae. This control was used to account for any reduction in waste weight due to water evaporation or bacterial decomposition. The daily waste reduction owing to black soldier fly larval development was corrected by this dehydration loss. Daily waste reduction was measured as wet weight and obtained using the calculation: (initial waste diet given to larvae in grams) − (amount of waste diet left over the next day in grams) − (waste diet loss in control in grams).

Six replicates were conducted, with each replicate originating from one generation of black soldier fly. The order of diet and larvae sampled were in a Latin square pattern. Nutritional analysis was conducted on the six samples of organic waste by Maxxim Analytics, Mississauga, ON, Canada. Prepupae samples were sent to AGAT Laboratories, St. Laurent, QC, Canada, for nutritional analysis.

Statistical Analysis. The waste reduction was recorded as the amount of waste reduced in grams per 10 larvae per day. Waste reduction (consumption) over time was analyzed with a generalized linear model with gamma distribution using waste reduction as the response dependent variable, day as a covariate predictor, and waste diet as a factor predictor. Waste reduction (consumption) measurements were recorded daily and, therefore, as the larval aged. Day (or larval age) is used as a covariate predictor for waste reduction (consumption). Unhandled larvae weight and length was compared by analysis of variance with a least significant difference-corrected post hoc means separation. All statistical analyses were performed by PASW Statistics 18.0 and 20.0 (SPSS Inc., Chicago, IL).

Results

Results of the generalized linear model demonstrated a significance of waste diet (Wald's chi-square = 56.369; df = 5; $P < 0.001$), day (Wald's chi-square = 1016.725; df = 1; $P < 0.001$), and waste diet × day interaction (Wald's chi-square = 91.527; df = 5; $P < 0.001$). Parameter estimates are shown in Table 1. With the exception of pig liver (B = −0.447), more waste was consumed overall than a standard poultry feed. Larvae fed on fruit and vegetable waste consumed almost

Table 1. Parameter estimates determined by generalized linear model gamma distribution regression

Parameter	B	Wald's chi-square	df	P value
Standard poultry feed	0[a]	–	–	–
Pig liver	−0.447	3.553	1	0.059
dPig manure	0.446	4.975	1	0.026
Kitchen waste	0.679	8.409	1	0.004
Fruits and vegetables	0.989	21.890	1	0.000
Fish rendering	0.742	11.159	1	0.001
Day	0.167	195.104	1	0.000
Standard poultry feed × day	0[a]	–	–	–
Pig liver × day	0.025	2.046	1	0.153
Pig manure × day	−0.082	37.162	1	0.000
Kitchen waste × day	−0.011	0.398	1	0.528
Fruits & vegetables × day	−0.062	17.967	1	0.000
Fish rendering × day	−0.054	11.956	1	0.001

[a] Set to zero because this parameter is used as a reference for comparison to other parameters.

Note: B is the regression coefficient. "X" represents the interaction of waste type and day. The top part of the table represents cumulative waste consumption and the lower part represents the waste type and day interaction (consumption per day). Statistical analysis performed by PASW Statistics 18.0 and 20.0 (SPSS Inc., Chicago, IL).

double (B = 0.989) the amount than those fed on a standard poultry feed. Although larvae fed manure, kitchen waste, fruits and vegetables, and fish rendering consumed more waste than the standard poultry feed, the rate at which they consumed it was slower than the standard poultry feed. Similarly, with the exception of pig liver (B = 0.025), the rate of waste reduction for the remaining waste is slower than the standard poultry feed.

Final larval weight (Fig. 1; $N = 36$; $F_{5,30} = 6.055$; $P = 0.001$) and length (Fig. 2; $N = 36$; $F_{5,30} = 4.396$; $P = 0.004$) differed for unhandled larvae when reared on different waste diets. Kitchen waste produced the heaviest larvae (679.88 mg per 3 larvae), with no difference between the remaining waste diets. Kitchen waste also produced the longest larvae (2.22 cm), followed by fruits and vegetables (2.16 cm) and manure (2.16 cm).

The waste diets that had the greatest energy, calorie, and fat content (Table 2) were fish and kitchen waste. Manure and feed diets had the lowest amount of energy. Manure also had the lowest amount of calories and fat. Based on the available data, larvae fed on fish and liver had higher nutritional content in terms of calories, proteins, fats, and carbohydrates than those fed on poultry feed (Table 3).

Discussion

Black soldier fly adults do not eat (Sheppard et al. 2002); therefore, they consume diets with the greatest fat content during larval stages to build up a fat body necessary to complete development and survive as adults long enough to mate and lay eggs (Tomberlin et al. 2002). Hence, black soldier fly larvae may prefer kitchen waste because it has the greatest fat and calorie content as compared with other wastes, excluding fish (Table 2). The high fat and calorie content in kitchen waste may have been responsible for producing the heaviest larvae. Although fish had a similar fat and calorie content to kitchen waste, black soldier fly larvae consumed fish at a slower rate (B = −0.054) than kitchen waste (B = −0.011). Fish renderings may also contain an accumulation of heavy metals. The fish-rendering waste was taken from Kingsville fisheries in Ontario, Canada, a location noted for high concentrations of certain heavy metals in bodies of water in Ontario (Gregory et al. 2005). *Drosophila melanogaster* (Meigen) (Diptera: Drosophilidae) larvae avoid foods with heavy metal contaminations when given a choice (Bahadorani and Hilliker 2009), as it interferes with larval development and adult survival. When forced to consume a resource with heavy metal contamination, *D. melanogaster* larvae consume less as compared with diets with no heavy metals (Bahadorani and Hilliker 2009). Likewise, black soldier fly larvae reared on a fish diet may fare worse than those reared on kitchen scraps if there are excessive levels of heavy metals in fish.

Fruits and vegetables had the greatest amount of waste consumption (B = 0.989) when compared to standard poultry feed, followed by fish rendering (B = 0.742), kitchen waste (B = 0.679), pig manure (B = 0.446), and pig liver (B = −0.447). Although larvae fed on fruits and vegetables consumed the greatest amount of waste when compared to standard poultry feed, the rate of waste consumption was lower than standard poultry feed (B = −0.062). This is because larvae fed fruits and vegetables took the longest to develop to the wandering stage, with the exception of those fed manure. In other words, in the later larval instars, larvae were consuming food for a longer period of time.

Manure had the lowest rate of waste reduction (B = −0.082) when compared to standard poultry feed, possibly because it contains the lowest amount of energy (kilojoules) and fat (Table 2). However, the total

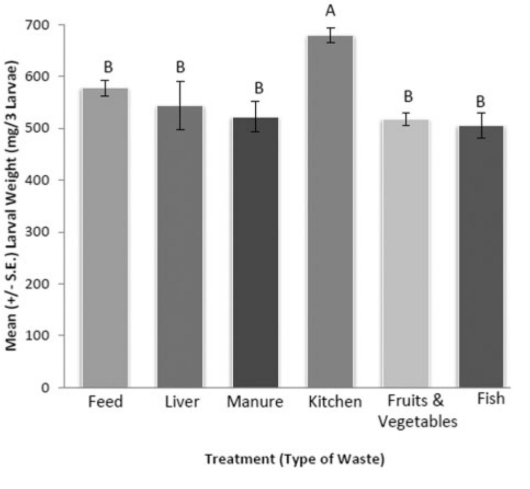

Fig. 1. Mean (±SE) weight for unhandled larvae reared on different organic wastes ($N = 36$; $F_{5,30} = 6.055$; $P = 0.001$). Means followed by the same letter are not significantly different ($P > 0.05$).

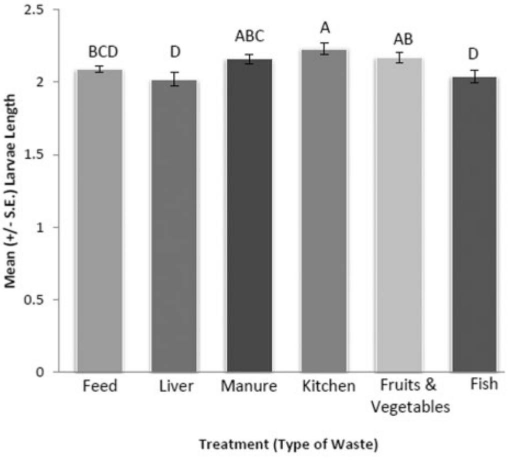

Fig. 2. Mean (±SE) length for unhandled larvae reared on different organic wastes ($N = 36$; $F_{5,30} = 4.396$; $P = 0.004$). Means followed by the same letter are not significantly different ($P > 0.05$).

Table 2. Nutritional analysis for six types of organic waste

Quantity per 100 g	Feed	Liver	Manure	Kitchen waste	Fruits and vegetables	Fish
KJ (kilojoules)	1,298.38	1,849.80	1,228.50	2,031.35	1,556.25	2,099.44
Calories	310.48	442.68	295.23	484.32	375.00	502.76
Proteins (g)	18.02	76.71	22.66	20.41	20.07	50.00
Fats (g)	2.52	12.84	1.40	19.58	1.55	36.18
Carbohydrates (g)	53.62	4.74	47.61	56.79	68.95	0.55

Note: Results are presented as dry weight for easier comparison. Wet weight analysis is presented in Nguyen et al. (2013). Analysis performed by Maxxim Analytics, Mississauga, ON, Canada.

Table 3. Nutritional analysis of prepupae reared on six types of organic wastes

Quantity per 100 g	Feed	Liver	Manure	Kitchen waste	Fruits and vegetables	Fish
Calories (kcal)	130	214	NA	NA	105	233
Proteins (g)	14.7	21	NA	21.2	12.9	19.4
Fats (g)	4.02	8.39	NA	NA	2.22	11.6
Carbohydrates (g)	8.75	13.7	NA	NA	8.38	12.7
Water (g)	66.5	55.3	NA	NA	71.8	53.4

Note: Some treatments did not yield enough prepupae samples for nutritional analysis and are represented by NA. The remaining results were obtained from 5–10 larvae samples from each treatment. Analysis performed by AGAT Laboratories, St. Laurent, QC, Canada, for nutritional analysis.

amount of manure waste reduction was 44% greater than that determined for the standard poultry feed. In comparison, the amount of waste reduced in kitchen waste, fish rendering, and fruits and vegetables was greater (67.9, 74.2, and 98.9%, respectively) than standard poultry feed. Although this was a small laboratory-based study, it shows that there is great promise for using black soldier flies as a potential agent for waste management. In a large-scale study by Sheppard et al. (1994), black soldier fly larvae reduced manure by ≥50% in a facility housing 460 hens. Furthermore, Nguyen et al. (2013) demonstrated that the mortality of larvae fed pig manure was not significantly different than that of control larvae. Perhaps, black soldier fly larvae can reduce other wastes on a large scale, and to an even greater extent than has been demonstrated with manure.

From the available data, liver and fish produced larvae that are more nutritious than those fed the standard diet (Table 3). This result is favorable because prepupae reared from these organic wastes can be used as feed for livestock animal. Prepupae fed on standard poultry feed, pig liver, fish, and fruits and vegetables in this experiment contained less protein and fat than previously reported (Hale 1973, Sheppard et al. 1994, Newton et al. 2005). This could be explained by the limited food given to the larvae in this study, which were only fed when they had consumed and dried out previous given waste.

Black soldier flies consumed and reduced all five diets that were specifically chosen to give the widest range of organic waste possible, ranging from an all-meat diet to an all-vegetable diet. With the exception of larvae fed kitchen waste, larvae that were produced were approximately the same length and weight as larvae fed the standard feed. Kitchen waste produced longer and heavier larvae. In addition, larvae fed kitchen waste have a similar developmental time when compared with that of control larvae (Nguyen et al. 2013). Larvae that were fed fish and liver diets had higher nutritional content than control larvae. This demonstrates that black soldier fly larvae can successfully be used to reduce organic waste and produce valuable nutritious prepupae as animal feed. Future steps should include testing for possible bioaccumulation of heavy metals and toxins in black soldier fly larvae before they are to be used as animal feed.

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