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BLACK SOLDIER FLY LARVAE FOR ORGANIC WASTE TREATMENT – PROSPECTS AND CONSTRAINTS

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ABSTRACT

Larvae of the black soldier fly, *Hermetia illucens* L. (Diptera: Stratiomyidae), may be used in low and middle-income countries to transform organic waste into valuable animal feedstuff: in the form of their last larval stage, the so-called prepupa. Revenues from sales of this potential animal feed can cover parts of the waste collection costs. Our research studies the prospects of this emerging technology, evaluates its constraints and responds to open research questions by means of lab scale experiments in Switzerland and Thailand and by conducting pilot field trials in Costa Rica. We conclude that the use of black soldier fly larvae has a great potential in organic waste management, be it the treatment of market waste, municipal organic waste or dewatered faecal sludge. Certain limitations exist, especially regarding the presence of heavy metals in the feed material, which negatively influence life history traits of the fly population and can accumulate in the prepupae.

INTRODUCTION

Waste management in developing countries

Due to rapid urbanisation, changes in demographics and consumer behaviour, municipalities and decision makers are confronted with new challenges in solid waste management. Over the past decade, numerous cities have increased their efforts at finding sustainable solid waste management solutions, especially in developing integrated solid waste management strategies, including construction and operation of sanitary landfills. To cover part of the increasing waste management costs, it comes as no surprise that scavenging, or in other words, valorising recycling activities, has turned into an income-generating activity conducted by the formal resource management authorities or performed jointly with the informal sector. In Ankara, Turkey, for example, scavengers collect and sell to middle men 50% of the recyclables produced by households, commerce and trade, yielding a total of about USD 50,000/day (Ali, 2002), and at least 150,000 waste pickers throughout Delhi's waste management system divert more than 25% of all waste generated into recyclables, thus saving the municipal authorities substantial costs (UN-HABITAT, 2010).

Since it is based on a purely money-driven process, it is not surprising that waste products already utilised in an existing market have a higher recycling rate than products to date regarded as worthless, such as the municipal organic waste fraction. In Quezon City, Philippines, for example, 33% (240,000 tonnes) of the total annual waste generated is reused by the formal and informal sectors. However, the recycled organic fraction accounts for only 14,000 tonnes (UN-HABITAT, 2010) – an example typical of countless municipalities in developing countries. The main reason for this lack of interest is the effort required to collect, separate and transform organic waste, eventually leading to a relatively small profit. With compost, for example, the product generated is handicapped by high transport costs in relation to product value, a competitive chemical fertiliser market or unfair regulations and policies (e.g. subsidies for chemical fertilisers) (Rouse et al., 2008). Generation of biogas from municipal organic waste is also a widespread technology at household level, particularly in India and China. However, economically viable middle and large-scale projects are often hindered by a lack of framework conditions for use and sale of the gas itself or its secondary products (electricity, heat). Efforts are therefore necessary to impart not only an idealistic value to the organic fraction, focusing on its nutrient recovery and environmental protection potential, but also to emphasise its inherent economic value.

Another central issue is the management of faecal sludge (FS). FS accumulating in septic tanks, latrines and other on-site sanitation facilities, contains high levels of nutrients and also pathogens. Despite its nutritional value, sludge generated in urban and peri-urban areas is frequently not reused in agriculture. The reasons are attributed to long distances between sludge producers and potential users of the treated sludge and to its complex treatment that reduces the economic viability of proper faecal sludge management. In Thailand for example, only 20% of the municipalities operate sludge treatment plants. In most cases, sludge is discharged into surface waters or reused without adequate treatment as soil conditioner and nutrient source in (peri-urban) agriculture. Such practices expose farmers and consumers alike to considerable health risks from the extremely high pathogenic contamination of the sludge.

Waste treatment by black soldier fly larvae

Conversion of organic waste by larvae of the black soldier fly, *Hermetia illucens* L. (Diptera: Stratiomyidae) into versatile prepupae is an interesting recycling technology, with a potential to give waste the aforementioned value.

Hermetia illucens is widespread in tropical and warmer temperate regions between about 45°N and 40°S (McCallan, 1974; Üstüner et al., 2003). Its larvae feed on different decaying organic material, such as rotting fruits and vegetables, animal manure and human excreta. The last larval stage, the so-called prepupa, migrates from the feed source in search of a dry and protected pupation site. Pupation occurs within the larval skin and the adult emerges after about 14 days. The adults are rather lethargic and poor flyers. Females mate two days after emerging and oviposit into dry cracks and crevices adjacent to a feed source. Due to the relatively long period between oviposition and eclosion (3–4 days), eggs are never laid directly onto the moist rotting material. During its adult stage, *H. illucens* does not feed and relies solely on its body fat reserve. Consequently, the fly does not come into contact with any degrading or fresh organic material including foodstuffs, and can therefore not be regarded as unsanitary or a vector of diseases (Leclercq, 1997; Schremmer, 1986).

Once hatched, larvae start to feed on the waste, thus achieving a dry mass volume waste reduction of ~55% (Myers et al., 2008; Newton et al., 1995; Sheppard, 1983). Due to high larval densities and the voracious appetite of the larvae, fresh material is processed extremely fast and bacteria growth suppressed or restrained, thereby reducing production of bad odour to a minimum.

An additional advantage of *H. illucens* is its capacity to repel oviposition of female house flies (Bradley and Sheppard, 1984), a serious disease vector especially in developing countries, where open defecation and inappropriate sanitation account for dangerous sources of pathogens (Graczyk et al., 2001). Under ideal conditions with abundant food sources (i.e. waste deposits), larvae can mature in two weeks. However, food shortage and low temperatures can extend the larval period up to four months (Furman et al., 1959). This great flexibility in their life cycle can be very helpful in managing populations during periods of waste shortage and in storing larvae to incubate a new population.

The prepupae, the last immature stage, show a pronounced migratory habit. They need to leave the food source to successfully pupate into adult flies. At this stage, the prepupae are at their maximum size, exhibiting large protein (36–48%) and fat (31–33%) contents to sustain them through metamorphosis (Hale, 1973; St-Hilaire et al., 2007; Stamer, 2005). This final instar shows slight morphological changes compared to the feeding larva. Its labrum, for example, is bent down like the beak of an eagle. It is used as a hook to pull them to a suitable pupation site (Schremmer, 1986). In facilities designed for waste management and prepupae collection, larvae climb up a ramp (30–45°) out of a rimmed container to eventually end in a collecting vessel attached to the end of the ramp. The yield of these energy-rich prepupae renders this technology so appealing to waste managers.

Products

Today, animal feed production strongly relies on protein and fat derived from forage fishery. In 2002, fishmeal and fish oil were primarily used worldwide for intensive food production, i.e. 24% for pigs, 22% for poultry and 46% for aquaculture (Alder et al., 2008). However, civil society and retailers are increasing their pressure on aquaculturists and poultry farmers to improve overall sustainability of fishery resources. Consequently, diminishing global supplies of wild forage fish and rising market prices for fishmeal have prompted the animal feed industry in recent years to look for alternative protein sources. Early studies with *Hermetia illucens* larvae and prepupae fed to poultry, pig and fish revealed promising results with regard to replacing fishmeal (Bondari and Sheppard, 1987; Hale, 1973; Newton et al., 1977). A recent study by St-Hilaire et al. (2007) working with rainbow trout, *Oncorhynchus mykiss*, endorsed these early findings but also found that the fish contained reduced levels of omega-3 fatty acids. Newton et al. (2005) even replaced 50% of commercial fish food with prepupae without negative effects on the growth of channel catfish fingerlings. However, all authors identified the need for improvement concerning the formulation of the feed, especially as regards the protein, fat and fibre ratio. However, the different compounds (protein, fat, chitin) could be fractionated and sold separately instead of using prepupae as one product. This would not only make formulation of animal diets easier, the different fractions could also be sold on specific markets, fetching higher prices. Newton et al. (2005) propose, for example, to extract the fat and convert it into biodiesel. They state that if the oil from soldier fly prepupae raised on pig manure were converted into biodiesel, it would yield as much energy as methane production from the same amount of manure.

Chitin is a further valuable fraction. The cuticle of insects is composed of chitin in a matrix with cuticular protein, lipids and other compounds. Chitin is of commercial interest due to its high percentage of nitrogen (6.9%) compared to synthetically substituted cellulose (1.25%). This makes chitin a useful chelating agent for products in medicine, cosmetics and even biotechnology (Kumar, 2000). Yet, the economic feasibility of extracting chitin from soldier fly prepupae has still to be assessed.

Besides the yield of prepupae, the black soldier fly treatment process generates a second product, i.e. the residue or digestate. Larval and bacterial activity reduces not only the dry mass but also several nutrient contents such as nitrogen or phosphorus. In pig manure, 80.5% of total nitrogen and 75.7% of phosphorus are removed (NC State University, 2006). Experiments with cow manure showed a nitrogen reduction of 43%, and 67% of the phosphorous was transformed into larval biomass (Myers et al., 2008). A possible designated use of this residue is application in agriculture, similar to compost or subsequent processing in a biogas facility. However, first growing experiments with larva residue from pig manure did not reveal promising results pertaining to performance of basil (*Ocimum basilicum*) and Sudan grass (*Sorghum sudanese*) grown on mixtures of BSF residue with either clay or sand (Newton et al., 2005). The question is to what extent can the product "residue" contribute to the revenue of a soldier fly treatment facility, or should it be regarded as a necessary evil whose impact on the environment has to be kept to a minimum.

Research gaps

Combination of waste treatment capacity together with generation of a valuable product makes the black soldier fly technology a highly promising tool for waste management in low and middle-income countries. It offers small entrepreneurs the possibility of income generation without high investment costs, and concurrently reduces the environmental impact. Yet, despite ample research on various topics geared to commercial waste treatment using *H. illucens*, initiatives for upscaling this technology are scarce and only few studies centre on developing countries (Hem et al., 2008; Lardé, 1990) or examine food scraps, household waste or faecal sludge as a feed source (Newby, 1997; Warburton and Hallman, 2002).

The objectives of our work were therefore to:

i) understand the key biological and physico-chemical processes during the life cycle of the black soldier fly, *Hermetia illucens*, especially its applicability in a waste processing unit.

ii) examine decomposition of organic waste streams, particularly as regards treatability of faecal sludge and municipal organic waste.

iii) assess possible obstacles and limitations in the context of low and middle-income countries.

iv) facilitate replication and dissemination of this technology by acquiring experience with medium-scale studies in Costa Rica in close collaboration with local researchers and implementation partners.

MATERIALS AND METHODS

Laboratory experiments under controlled conditions were conducted at the Swiss Federal Institute of Aquatic Science (Eawag), *inter alia,* using standardised feed spiked with different concentrations of cadmium, lead, and zinc to assess potential restrictive uses of the prepupae in animal feed in order to preclude bioaccumulation. Find detailed descriptions in Diener et al. (2009) and in Diener et al. (2010).

Experiments to assess the digestibility of faecal sludge were conducted in a laboratory of the Asian Institute of Technology (AIT), using larvae derived from a soldier fly colony raised in a small greenhouse (3 m x 3 m), equipped with an automatic water spraying system (Nguyen, 2010). The sludge, originating from nearby septic tanks of the municipal service providers, was dewatered (63% H_2O) in a small-scale drying bed. To determine digestibility and optimal mixing ratio of faecal sludge and market waste, larvae were fed different ratios of these waste products (0%, 25%, 50%, 80%, and 100% FS) every three days until all larvae had transformed into prepupae.

The research study site for the medium-scale experiments was located on the campus of the EARTH University (Escuela de Agricultura de la Región Tropical Húmeda) in Guácimo, Costa Rica. The experiments were carried out in a former chicken pen (30 x 8 m) roofed by a corrugated metal sheet and enclosed by a wire net. A population of the black soldier fly, *Hermetia illucens* L., was maintained in a small green house (2 x 3 x 2.5 m), referred to as "moscario", roofed with transparent plastic foil fitted with a sun shading net and nylon netted sidewalls. The moscario was placed on a meadow, exposed daily to direct sunlight for about eight hours. The experiments were conducted in trays (80 cm x 200 cm x 30 cm), the so-called "larveros", built with zinc-coated steel sheets. For exiting prepupae, two ramps at a 28° angle led from the base plate (100 x 80 cm) to the upper end of each shorter side panel. A plastic pipe (∅ 11 cm x 94 cm) was fixed along the top of this edge. A slit (5 x 80 cm) cut into the pipe allowed migrating soldier fly prepupae to enter and crawl along the pipe leading to downspouts at each end of the pipe from where they fell into harvesting containers. To avoid ant invasion, the larveros had to be placed on pieces of bamboo (∅ 10–15 cm x 25 cm) standing in water-filled plastic pots.

Organic waste generated by the residents of the EARTH university campus was used for the experiments. The content of several bags of the source-separated organic waste (approximately 20 kg) was mixed thoroughly to achieve certain homogeneity and then added to the larveros according to the defined feeding regime.

RESULTS AND DISCUSSION

Laboratory experiments confirmed, on the one hand, the predicted larvae's potential to reduce waste and produce protein, thus allowing a balanced trade-off between high prepupal weight and high material reduction. On the other hand, the lab results relating to absolute prepupal weight and waste reduction were lower than the values given in the literature, thereby turning operation of an economically sustainable treatment facility into a rather questionable issue.

Fortunately, these concerns were unfounded as revealed by the successful field experiments conducted in Costa Rica. Waste reduction exceeded all our expectations despite local stumbling blocks, such as a fly colony weakened by zinc poisoning and a far lower larval density. Instead of waste reduction values around 40% as achieved in the laboratory, the household waste could be reduced from 65% to 75% (Table 1). Even the prepupal weight attained under field conditions was far higher than the value assessed in the laboratory. Prepupae grown on municipal organic waste weighed 195–220 mg (wet weight) – even prepupae fed in the laboratory experiments with the highest waste ration weighed 25% less (157 mg).

Table 1: Daily feeding rate (wet weight), larval development time (egg to prepupa), prepupal dry weight and relative material reduction during the entire experiment using different feed sources to feed larvae of the black soldier fly, *Hermetia illucens*. MW = market waste. MOW = municipal organic waste. Numbers in brackets = Standard deviation

Feed source	Feeding rate	Development time	Prepupal dry weight	Dry weight reduction of feed
	mg/larva/day	Days	mg	Percent
Chicken feed	25	32.7	39.1 (3.3)	37.3 (0.9)
Chicken feed	100	16.6	48.0 (3.5)	41.8 (1.1)
Chicken feed	200	15.9	63.3 (11.0)	26.2 (2.4)
Faecal sludge (FS)	167	27.0	18.1 (0.6)	54.7 (1.3)
FS:MW = 1:1	167	18.0	38.7 (0.6)	66.6 (0.8)
MW	167	18.0	59.9 (3.4)	59.4 (0.6)
MOW	507	n.a.	83.5 (6.9)	68.0 (3.4)

Concerning the treatability of faecal sludge, the larvae of the black soldier fly were not only able to survive and even develop in pure faecal sludge, but were also capable of significantly reducing the sludge biomass. Nonetheless, the larvae developed much faster when market waste was added to the faecal sludge to enhance the nutritive value of the larvae's feed source (Figure 1). The resulting prepupae were also much fatter than when feeding on faecal sludge only. The combination of faecal sludge with market waste in a 50:50 ratio promises to be a good combination of prepupal biomass production and efficient waste reduction.

Laboratory experiments on the fate of heavy metals present in the feed revealed highly interesting accumulation patterns varying according to metal type and concentration. To put it in a nutshell: cadmium was accumulated, lead suppressed and zinc was kept at a more or less constant level. Accumulation of heavy metals and the way the insects deal with them are of special concern, particularly as regards sustainability of this technology, which aims at being productive while generating a non-toxic product. Many insects possess a natural detoxification mechanism requiring, however, additional energy spent at the cost of growth and/or health. This is being reflected in an alteration of at least one of the important life history traits, such as decreased body mass, life span, reproduction, resistance to other stress factors or decreased resilience in general (Maryanski et al., 2002). The consequences of such a fight against disruptive factors were observed during the field experiments in Costa Rica, where the fly population struggled with a high zinc concentration. It somehow managed to survive but seemed extremely weak and susceptible to additional stress factors. Avoiding contaminated food sources, though highly recommended, may not always be possible. Therefore, to provide a somewhat optimum environment, any further perturbing factors should be avoided.

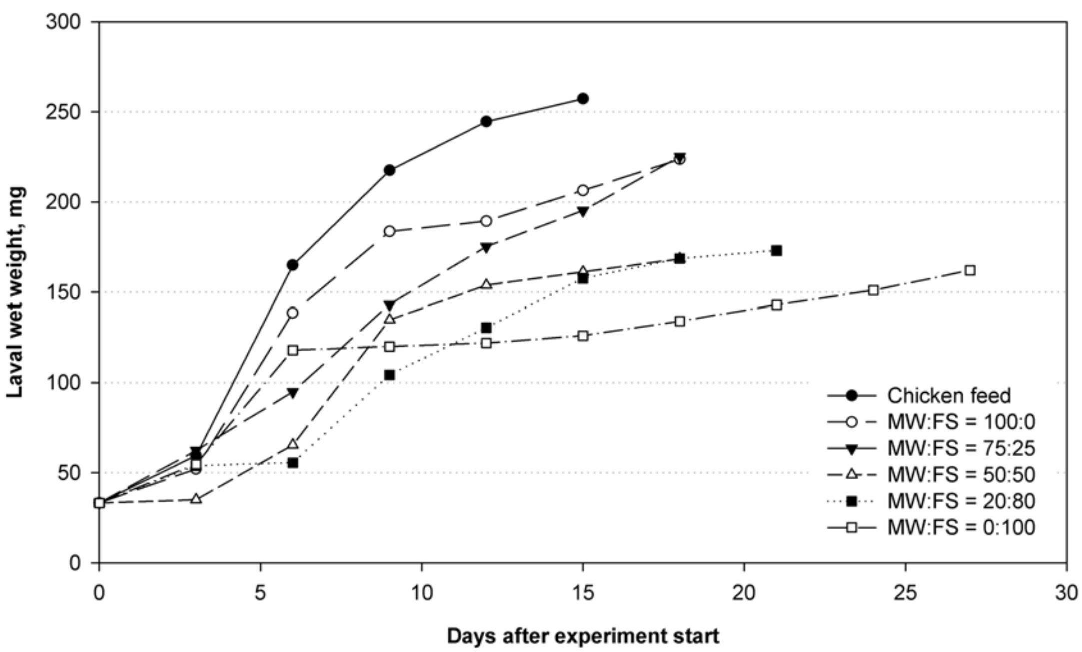

Figure 1: Weight gain of black soldier fly larvae fed with chicken feed or different mixing ratios of market waste (MW) and faecal sludge (FS)

Use of prepupae and residue derived from heavy metal contaminated sources may understandably be restricted. Concentrations will possibly accumulate along the food chain, either via the prepupae fed to chickens, fish or pigs or through the residue ending up in commercially sold vegetables. A process allowing separation of the heavy metals from the products (prepupae and residue) should be developed. In the case of the prepupae, separating the different fractions, such as protein, fat and chitin and using only the uncontaminated parts could provide a possible solution.

The residue from the field trials fell short of our expectations. The material was very wet (82–86% H_2O) and gave off a foul-smelling odour. Whole pieces of organic waste, such as mangoes or bananas, remained untouched due to the stagnating liquid at the bottom of the larveros, thus creating anaerobic conditions. Such conditions hinder larval access to the food source, thus, reducing yield and inhibiting waste reduction. Furthermore, handling of the residue is hampered due to its sticky consistency and foul odour. The system's vulnerability is also enhanced due to ongoing and unstable biological processes. Only the combination of a well designed drainage system and appropriate feeding regime (chopped food, small quantities with high loading frequency) will lead to a steady treatment process and an appropriate residual product. Yet, the residue will most likely have to be post-treated through composting/vermicomposting to ensure biological stability prior to its application as a soil conditioner, or its remaining energy potential possibly exploited by feeding it to a biogas plant.

CONCLUSION

The study at hand confirms the application potential of the black soldier fly in solid waste management. However, we are dealing here with a technology whose delicate equilibrium is based on living organisms. However, *Hermetia illucens* is an extremely resistant species capable of dealing with demanding environmental conditions, such as drought, food shortage or oxygen deficiency. Owing to their robustness, survival of the species as a whole will not be endangered within a region, yet, a waste source turning anaerobic, temperatures reaching lethal values or elevated heavy metal concentrations exceeding a certain threshold level may prove fatal to the affected larva population. Even a partial collapse of a treatment plant's population can have serious economic and environmental consequences. Contracts with waste suppliers and product purchasers may be unfulfilled and, thus, the collected waste disposed of untreated. The challenge of future research will therefore be to provide sound data on the biological treatment processes and the environmental conditions required by the insects to enhance performance of the treatment facility and, thus, increase financial output. This will strengthen resilience of the treatment plant and the waste management plan in which the BSF unit is embedded. In addition, research will have to take into account effects deriving from up-scaling and finally a refinement of design and operation of the facility to ensure an optimisation of profitability. Such research must occur iteratively, involving plant operators, researchers and regional planners, with closely knit information exchange networks to ensure rapid response to emerging new developments and challenges.

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