Production of fish feed from vegetable waste

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Funding, Purpose and Disclaimer

This project has been funded by HAL using levy funds from the Australian vegetable industry and matched funds from the Australian Government.

The purpose of this project was to evaluate the potential for using vegetable waste to grow insects, which could then be used to wholly or partially replace wild caught fishmeal in aquaculture feeds. Primarily a desktop study, the project also conducted some small initial trials examining the suitability of different vegetables for producing black soldier fly larvae and describes some of the issues that need to be addressed in commercializing this method.

Contents

1 Media Summary

Australian consumers love fish and seafood! Consumption has doubled in the last 10 years and is predicted to continue to grow. However, most wild fisheries are already maximized or in decline. The only way to meet this demand is therefore through increased aquaculture.

However, most aquaculture species are still fed, at least in part, on fishmeal made from wild caught fish. This is not only unsustainable, but a major factor limiting increased production. Meal made from insect larvae have been proposed as an alternative. Insects are high in protein and fat, can be reared on waste products and are part of the natural diet of some farmed fish species.

This project has examined the potential to use vegetable wastes to grow insect larvae, which can then be used in aquaculture feeds. Of the insects studied, black soldier fly (BSF) appears to be a clear frontrunner. Larvae can live on vegetables alone, 'self harvesting' when they are fully mature. Adult flies are found naturally in Australia. They are not pests and don't carry disease, living long enough only to mate and lay eggs.

We have conducted a series of small trials finding out how easily BSF can be reared in captivity, what vegetables they can eat, and how the quality of dried larvae compares to commercial fishmeal.

An initial colony of BSF was readily generated from local wild populations and grown through to adults. Although adults have been widely reported to not eat, our flies only mated and laid eggs once they were provided with apple juice. Feeding trials with 2nd generation larvae showed that pumpkin, carrot, eggplant, capsicum and processed vegetable sludge were all readily consumed. They could live on lettuce for only a short time, and these larvae had a much higher water content than those fed other foods. Cauliflower and broccoli were not suitable and sweet potato was non-preferred.

It was difficult to calculate the exact amount of feed required to produce the maggots as they liquefy feed before eating it, combining waste with uneaten food. Estimated feed conversion rates of vegetable:larvae ranged from 4.9:1 to 2.0:1, averaging 3.3:1 (dry weights). This means that around 25g fresh pumpkin or 30g fresh carrot would be needed to produce 1g dried larval meal. The ratio was further improved by adding ground flax seed to the diet – this doubled the rate of weight gain and reduced the volume of fresh feed required by around 70%.

An economic analysis indicates that BSF are currently a risky option for an individual vegetable grower. Considerably more research is needed before this method can be confidently commercialized. However, as the price of wild caught fishmeal continues to increase financial viability becomes more likely. Commercial facilities are now being developed in other countries. These will help provide better guidance about how we can grow and use these fascinating animals.

2 Technical Summary

Consumption of fish and seafood in Australia has doubled in the last 10 years and is predicted to continue to increase. However, most wild fisheries are already maximized or in decline. The only way to meet this demand is therefore through increased aquaculture. One factor limiting aquaculture is the continued reliance on wild caught fish to produce fishmeal. Much research has focused on replacing fishmeal with animal and/or plant based products, with only partial success.

Insect based meals may offer an alternative. Insects are high in protein and fat, can be reared on a range of waste products, have a high feed conversion rate and are part of the natural diet of some carnivorous fish species. This project has examined the potential to use vegetable wastes to rear insect larvae, which can then be used as components of aquaculture feed.

Initially a desktop study was conducted on four species with known potential; black soldier fly (*Hermetia illucens*), yellow mealworm (*Tenebrio molitor*), superworm (*Zophobas morio*) and housefly (*Musca domestica*). Of these the black soldier fly (BSF) appeared to be clearly the most suitable. Larvae can live on vegetables alone and 'self harvest' at maturity. Adult flies are not pests and do not carry disease, living only long enough to produce the next generation. They have already been found suitable for feeding to a number of fish species and are currently being commercialized in several countries.

A series of trials were conducted examining the issues involved in setting up a BSF colony, testing suitable vegetables to use as feedstocks, and analyzing the quality attributes of the dried meal produced. An initial colony was readily generated from wild populations and larvae reared through to pupation and emergence. Encouraging adults to mate and lay eggs under controlled conditions was more problematic, but was overcome by providing adult flies with a sugar source and fruit / vegetable wastes in which to oviposit.

Larvae readily consumed pumpkin, carrot, eggplant, capsicum and processed vegetable sludge. Lettuce was suitable for short time feeding only; more than 1 week increased mortality. Cauliflower and broccoli were not suitable and sweet potato was non-preferred. Dry weight of larvae was closely related to dry matter content of feed.

It was difficult to accurately calculate feed conversion rates as larvae liquefy feed before eating it, combining waste with uneaten food. Estimated feed conversion rates of vegetable:larvae ranged from 4.9:1 to 2.0:1, averaging 3.3:1 (dry weights). This is consistent with previously published results and means that around 25g fresh pumpkin or 30g fresh carrot would be needed to produce 1g dried larval meal.

The ratio was further improved by adding ground flax seed to the diet – this doubled the rate of weight gain and reduced the volume of fresh feed required by around 70%. Larvae fed this diet contained >64g.kg^{-1} Omega 3 fatty acids, which could add to their value for aquaculture feed.

This area of research is in its infancy; more needs to be known about the effects of diet, nutritional attributes of the larvae and optimizing the process for use in different aquaculture feeds if this is to move to commercialization. Although investment in BSF would currently be a risky venture for an individual vegetable farmer, this industry has considerable potential and may develop in the future as fishmeal prices continue to rise.

3 Recommendations

This project has demonstrated that black soldier fly larvae can be reared successfully on a range of different vegetable crops. While some of the results appear positive and promising, there is a clear need for a much larger research project to develop this further if the method is to find commercial application. In effect, this project has raised at least as many questions as were answered.

A larger research trial would examine:

- The effect of different feed combinations on larval growth and quality
- A full analysis of larvae in terms of the presence and concentrations of different amino acids and fats, as well as other componenets such as chitin
- Optimising mating and oviposition
- Streamlining development time, temperature and harvesting for maximum yield and quality
- Suitability of meal products in different feeds for various aquaculture species

Such a large research project needs to be funded using University or National based funding, such as an ARC (Australian Research Council) linkage grant or CSIRO flagship. It needs to be broader than the vegetable industry, preferably involving a large commercial partner such as one of the aquaculture feed suppliers, and possibly overseas expertise.

It is also recommended that any IP developed from this specific project should be protected for the benefit of HAL and the Australian vegetable industry.

4 Introduction

4.1 The rise of aquaculture

Consumption of fish and seafood in Australia has doubled in the last 10 years and currently stands at around 13kg per person year. This has been predicted to increase to 17kg by 2020 and 25kg per year by 2050, giving a total domestic requirement of 1.15kt annually. Given falling wild catches, aquaculture needs to double by 2020 and double again by 2050 to meet this demand [1].

In the period 1970–2008, the production of fish from aquaculture increased at an average annual rate of 8.3 percent. This is in comparison with poultry and livestock meat production at an average rate 2.7% per year (FAO 2010). Currently, about one third of aquaculture production consists of highly carnivorous fish e.g. salmon, sea breams, barramundi. If the aquaculture sector is to sustain its current growth rate, then the supply of production inputs will also have to grow at similar rate to meet demand.

One of the major factors restricting increased use of aquaculture is that most production systems rely on feeding high value aquaculture species on relatively low value wild caught fish. This is not sustainable in the long term, and has led to a search for alternative sources of high protein, high fat food sources. These have included cottonseed meal, legume crops such as lupins and soy, meat and bone meal and poultry wastes[2].

Plant-based fish foods have problems with poor palatability, presence of anti-nutrients (e.g. phytic acid), intolerance to complex carbohydrates and deficiencies in essential amino acids. Animal-based foods are better but also have problems such as poor consumer acceptance, high levels of saturated fats, absence of omega 3 fatty acids and issues with food safety from rendered animal meal.

4.2 Insects as fish feed

Insect-based protein meals offer an alternative to plant and animal-based fish food as ingredients in fish food for aquaculture. Species that may have potential include:

- Black soldier fly (*Hermetia illucens*)
- Yellow mealworm (*Tenebrio molitor*)
- Super worm (*Zophobas morio*)
- Housefly (*Musca domestica*)

[1] Kearney, B., Foran, B., Poldy, F., Lowe, D. 2003. Modeling Australia's fisheries to 2050: Policy and management implications. Fisheries Research and Development Corporation. Final report.

[2] Nguyen TN, Davis, D.A. 2009. Evaluation of alternative protein sources to replace fishmeal in practical diets for juvenile Tilapia *Oreochromis spp*. Journal of the World Aquaculture Society. 40:114-121.

Each of these insects has its own characteristics, but all can be reared wholly or partly on vegetable wastes such as carrots, green leaves, and plant stems[3]. This report presents an initial review of what is known about cultivation of these insects in terms of lifecycle, reproduction, feed use efficiency and potential use as an animal or aquaculture feed.

4.3 Option 1 – Black soldier fly *Hermetia illucens*

This species appears to be a clear front-runner in terms of its usefulness as a feed source as well as its ability to thrive on vegetable wastes. There is a large body of information on this insect and much talk among researchers, aquaculture technologists and backyard enthusiasts as to its incredible potential value for the future. Discussions with aquaculture professionals have led to offers of free feeding trials – if a sufficient amount of material can be supplied (S Grierson, RothqueBio, pers. com.). Certainly this is an area that feed producers such as Ridleys and Skretting appear to be watching closely.

Much of the earlier research focus was on disposal of problem wastes, especially animal manures. This has led to generation of a reasonable amount of information on rearing and breeding this insect - processes which present a number of challenges. More recently, research appears to be focusing on use of BSF in aquaculture or poultry feed, as well as extraction of other components (such as oil) for additional uses.

Production of BSF from vegetable wastes therefore appears worthy of a detailed evaluation.

4.4 Option 2 – Yellow mealworm *Tenebrio molitor*

Mealworms have a long history of use as food for poultry, reptiles and fish. They are extremely easy to rear and breed in captivity, will consume a wide range of different feeds and can be separated from their food source reasonably easily. Despite this, there has been comparatively little consideration of their use in commercial aquafeeds.

Although mealworms are strongly attracted to vegetables, these can only form part of the diet. To do well, mealworms require a substrate of grains such as oats or wheat bran supplemented with a protein source such as yeast. Unless the grower can access a cheap source of these materials, it will be difficult to make this option financially viable.

4.5 Option 3 – Superworm *Zophobas morio*

Similarly to mealworms, superworms are already supplied commercially as feed for pet reptiles and birds. However, there has been little or no consideration of wider use in commercial feeds. This may be due to the labour intensive nature of their production as well as their relatively high chitin content. Also, although their large size makes them easier to handle than mealworms, they are slightly more difficult to rear and need relatively warm

[3] Li, LY, Zhao, Z.R., Liu, H. 2012. Feasibility of feeding yellow mealworm (*Tenebrio molitor* L.) in bioregenerative life support systems as a source of animal protein for humans. Acta Astronautica. In Press.

temperatures to do well. In addition, although vegetables are an important part of their diets, grains form the major component. So, as described for mealworms, they may not be a profitable option for vegetable farmers.

4.6 Option 4 – Housefly *Musca domestica*

The housefly needs no introduction, as it is not only the worlds commonest insect but also considered a major pest. This is partly due to its nuisance factor, but also because it carries disease. It can adapt to a wide range of environments and consume virtually any decaying organic material. Perhaps for that reason, there is significant interest in using housefly larvae to turn waste into high protein, high fat materials for animal and fish feeds.

While houseflies can live on decaying organic matter they perform better with the addition of putrescible wastes – such as abattoir wastes – or manures. There is at least one commercial facility producing housefly larvae from sewage sludge and abattoir waste, located in South Africa.

This would not appear to be a good use of vegetable wastes. To be commercially viable housefly larvae must be disposing of a waste that would otherwise cost money to get rid of. This is not the case with vegetable wastes.

In addition, there is likely to be strong resistance from local authorities and residents to establishing any housefly larvae production facility. The association between houseflies and disease also means there is likely to be resistance to using the meal, whatever the assurances provided.

Houseflies are therefore not considered further within this review.

5 Black soldier fly - *Hermetia illucens*

5.1 Key Points

Advantages

- Fast growth and development
- Efficient disposal of waste materials
- Larvae self harvesting at maturity and relatively easily processed
- Larvae / prepupae suitable for some high value uses, especially with refinement of culture and processing methods
- Frass suitable for lower value uses – saleable item
- Adult flies are short-lived and lack functional mouthparts, so no pest or disease issues
- Some commercial production now starting in other companies – expertise in setting up a facility is available

Disadvantages

- Difficult to rear through the complete lifecycle – specific requirements for mating and egg lay
- May have relatively low feed efficiency on high-moisture, low calorie value substrates (such as some vegetables)
- Unsuitable for some aquaculture species due to high chitin content
- Requires warm temperatures and high humidity – adds to cost if heating required
- Limited commercial application (so far) despite decades of promising research,
- More research still needed to
    - improve productivity,
    - link feedstock nutrition with fitness for purpose (eg Omega 3 addition)
    - optimise processing for maximum palatability and digestability
    - determine suitability for different aquaculture species

5.2 Natural distribution

Black soldier fly (*Hermetia illucens)* was originally a native of subtropical and temperate regions of the southern United States. However, international trade and the spread of intensive agriculture after WW1, have enabled it to spread to most countries. It is now mainly limited by latitude; around 40^{o} south and 40-45^{o} north.

Black soldier fly (BSF) was reportedly introduced into Malta in 1926, and since then has been found as far north as England and the Netherlands - where it is most likely a summer visitor. It is also widely distributed around northern Africa, South America[4] and Asia[5] . The insect has

[4] Copello A. 1926. Biology of *H. illucens*, the fly of Argentine beehives. Revista Soc. Ento. Argentina. 1:23-26.

[5] Kim J-G et al. 2008. Ecology of the black soldier fly, Hermetia illucens (Diptera:Stratmyidae) in Korea. Korean J. Appl. Ento. 47:337-343.

been present in Australia since at least 1915[6] and is also found in New Zealand, although the cooler climate means it is less common there.

5.3 Lifecycle and morphology

Adult BSF are a common backyard insect in many parts of Australia during the warmer months. These slender, black flies rather resemble wasps, but are unable to bite or sting. The flies do not carry disease, rarely enter enclosed spaces (such as the interiors of houses) and have only rudimentary mouthparts. As a result, although historically referred to as a pest species[4,7,8], there is little or no evidence of them negatively affecting humans.

BSF do not feed during their adult lives but live off the large fat deposits accumulated during the larval stage. Pre-pupae of BSF are approximately 35% fat and 42% protein. By comparison, housefly larvae are approximately 9-15% fat[9]. This is why housefly adults must feed soon after they emerge from their pupae, whereas BSF can survive for 2 weeks or even longer on water alone[17,17]. The fact BSF adults do not feed helps explain their voracious appetites as larvae, and the resulting high suitability of pupae as feed for other animals. Large larvae develop into longer-lived adults[14], increasing their ability to mate and lay more eggs.

Figure 1 - Adult black soldier fly

Mating usually occurs 2-3 days after adult flies emerge, with females ovipositing 1-2 days later[18]. Clusters of several hundred white eggs are laid in dry crevices close to decaying organic materials. Flies are most likely to oviposit under warm, humid conditions; this will be discussed in more detail later in this review. The eggs hatch after about 4 days at 27^{o}C[16].

Newly hatched larvae (larvae) are approximately 1.8mm long and are a dull white to cream colour. They are easily distinguished from other fly larvae by their obviously segmented

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[6] Callan EM. 1973. Hermetia illucens (L.) (Dipt., Stratiomyidae), a cosmopolitan American species long established in Australia and New Zealand

[7] Bradley GH. 1930. *Hermetia illucens*. A pest of sanitary privies in Louisiana. J. Econ. Entomol. 23:1012-1013.

[8] Meleney HE Harwood PD. 1935. Human intestinal myiasis due to the larvae of the soldier fly, *Hermetia illucens* Linne (Diptera, Stratiomyidae) in Tennessee. Amer J. Tropical Medicine. 15:45-49.

[9] Teotia JS Miller BF. 1974. Nutritive contents of housefly pupae and manure residue. Br. Poult. Sci. 15:177-182.

bodies. The distinctive row of short, bristly hairs on each of their 11 segments also helps identify BSF from other larvae.

Larvae pass through 6 developmental stages (instars). Insects in the last larval stage are called a 'pre-pupae', and may be up to 27mm long and 6mm wide. Pre-pupae are easily distinguished from other larval stages by their brownish colour and flattened shape. It can take less than 3 weeks or more than 3 months for larvae to pass through these 6 stages, with development rate being highly dependent on temperature, food type and food availability.

Figure 2 - Black soldier fly larvae feeding on capsicum

Once larvae reach the 6th and final stage (pre-pupae) they search for a suitable place to pupate. If food supply is limited they will wait until they reach a minimum of 35mg dry weight[10] before pupating. If food is not limited they can be double this size. Their natural instinct is to climb up and out from the damp, decaying organic matter in which they have been living and find somewhere dry. In artificial culture this can be exploited – escape ramps allow pre-pupae to leave the food mass and drop conveniently into a bucket for collection. This is a significant advantage of the species, as separating larvae from their food source is one of the major barriers to using other insect larvae in animal feeds.

[10] Diener S Zurbrugg C Tockner K. 2009. Conversion of organic material by black soldier fly larvae: establishing optimum feeding rates. Waste Management Res. 27:603-610.

Figure 3 - Self-harvested black soldier fly prepupae

The wandering pre-pupal stage lasts 7 – 10 days at 27^{o}C, during which time the larvae stop eating. Approximately 7 days more are required for actual pupation. Under natural conditions pre-pupae bury themselves lightly in soil. It has been found beneficial to provide pre-pupae with wood shavings or other light material rather than forcing them to pupate on a bare surface. This reduces the time spent roaming during the non-feeding pre-pupal stage, ensuring they are at maximum weight during pupation and resulting in a higher rate of adult emergence[23].

5.4 Mating and oviposition

In the wild, male BSF will generally congregate on trees and bushes at the edge of open spaces. Known as 'lekking' areas, males compete for optimum spots, grappling with each other mid-air until the weaker male leaves the area. The lekking sites attract virgin females seeking mates. An arriving female will "call" males, who compete for her attentions. Mating is generally on or close to the ground, with the male and female facing different directions[11] (Figure 4)

[11] Tomberlin JK, Sheppard DC. 2001. Lekking behavior of the black soldier fly (Diptera:Stratiomyidae). Florida Entomologist 84:729-730.

Figure 4 - Mating black soldier flies. The female (L) is larger than the male (R)

Mating presents a number of challenges in an artificial colony. Larger cages are needed to increase the probability of success; Tingle[12] reported that although mating was observed often in an outdoor cage measuring 3 x 6 x 1.8m, and occasionally in a 0.8 x 1.1 x 1.4m cage (also outdoors), when the smaller cage was moved indoors no mating occurred. No mating or egg collection occurred in cages measuring less than $1m^2$ under any conditions[12]. Other researchers report holding adults in 2 x 2 x 4m cages[19], 1.5 x 1.5 x 3m cages[18], $3m^3$ cages[13] and even free flying inside a small greenhouse[14] in order to ensure mating occurred. Barry[29] reported significant difficulty in getting flies to mate, with only a heated, $66m^3$ greenhouse proving suitable. While some have proposed that plants should be included inside the cages as lekking sites[11] this is not essential for mating to occur, so long as other conditions are suitable (Tomberlin pers. com.)

Another requirement for successful mating is strong light, preferably sunlight. Sheppard[19] reported that a minimum of 63 $\mu mol.m^{-2}.s^{-1}$ was required for mating with optimal results at more than 200 $\mu mol.m^{-2}.s^{-1}$. Although Zhang[15] reported that most mating occurred in the early morning, Kim[5] found that mating was most frequent during the day, when light was most intense (Figure 5). For this reason, mating is rarely observed during winter or on cloudy days, even in a heated greenhouse.

Attempts to provide artificial lighting have had limited success. Early attempts with either a 40 watt Gro-Lux® or 430 watt Pro Ultralight light system failed to elicit mating[18]. Although Zhang had some success using a quartz iodine lamp producing 135 $\mu mol.m^{-2}.s^{-1}$, mating rates remained only 61% of those in the sunlit controls, while the 160 $\mu mol.m^{-2}.s^{-1}$ rare earth lamp failed to stimulate any mating at all.

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[12] Tingle FC Mitchell ER Copeland WW. 1975. The soldier fly *Hermetia illucens* in poultry houses in north central Florida. J. Ga. Entomol. 10:179-183.

[13] Gobbi P Martinez-Sanchez A Rojo S. 2013. The effects of larval diet on adult life-history traits of the black soldier fly, *Hermetia illucens* (Diptera: Stratiomyidae). Eur. J. Entomol. 110:461-468.

[14] Nguyen TTX Tomberlin JK VanLaerhoven S. 2013. Influence of resources on *Hermetia illucens* (Diptera:Stratiomyidae) larval development. J. Med. Entomol. 50:898-906.

[15] Zhang J et al. 2010. An artificial light source influences mating and oviposition of black soldier flies, *Hermetia illucens*. J. Insect Sci. 10:202.

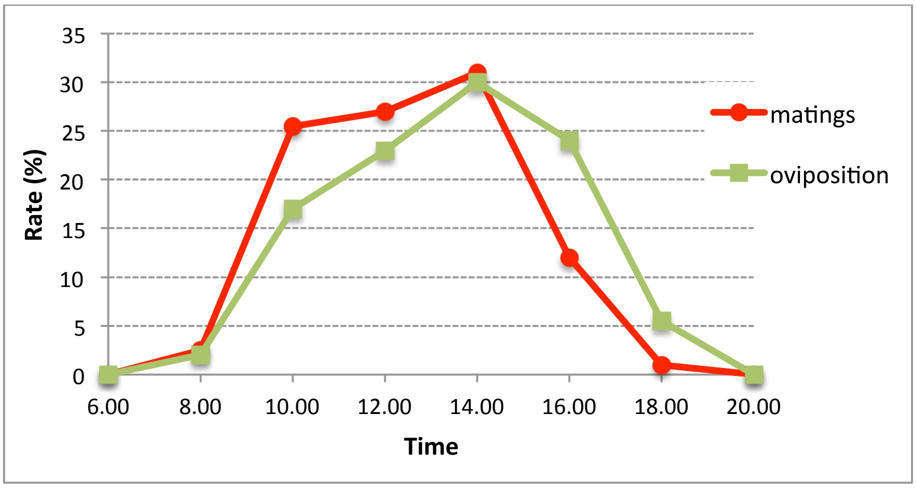

Figure 5 - Mating and oviposition times of H. illucens. Derived from Kim et al., 2008

Light also affects oviposition, with most occurring when light is brightest. Studying behavior in wild populations, Booth and Sheppard[16] found a clear peak in oviposition between 13:00 – 17:00pm. Similar results were reported by Kim[5] for a lab based colony (Figure 5).

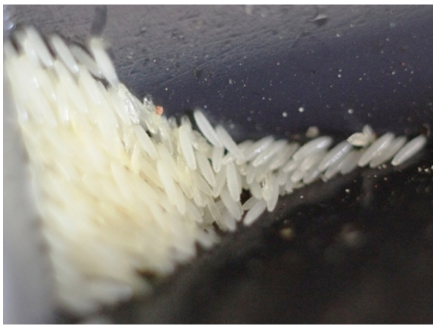

Figure 6 - A black soldier fly laying eggs (L) and an egg mass inside the crevice of a plastic container (R, photo by Andrei Sarbu)

The natural instinct of *H. illucens* is to oviposit in dry cracks close to moist, decomposing organic material (Figure 6). It has been found that the small openings (flutes) in strips or rolls of corrugated cardboard make highly suitable oviposition sites for this insect[16], with smaller size corrugates (3 flutes per cm) preferred[19]. The dry cardboard is usually positioned vertically over an oviposition attractant, such as wet Gainesville housefly diet or well moistened poultry layer mash. A single female may lay 300 - 600 eggs, with multiple females often ovipositing within the same flute[17].

Although a colony can be maintained at 22°C, no eggs are laid at this temperature[18]. Adults in laboratory colonies have been shown to mate and lay eggs at temperatures ranging from 24 – 40°C[19]. In the wild, 99.6% of oviposition has been reported to occur between 28-38°C[20].

[16] Booth DC Sheppard DC. 1984. Oviposition of black soldier fly, *Hermetia illucens* (Diptera: Stratiomyidae): eggs, masses, timing and site characteristics.
[17] Tomberlin JK Sheppard DC Joyce JA. 2002. Selected life history traits of black soldier flies (Diptera: Stratiomyidae) reared on three artificial diets.
[18] Tomberlin JK Sheppard DC. 2002. Factors influencing mating and oviposition of black soldier flies (Diptera Stratiomyidae) in a colony. J. Entomol. Sci. 37:345-351.

5.5 Larvae - temperature and humidity

Although BSF is essentially a tropical and warm-temperate species[20] the insect can survive an extremely wide range of temperatures. However, development rates are strongly temperature dependent.

The optimum temperature for larval development has been variously reported at 27 – 35°C. At 27°C the larval stage may last as little as 15-20 days[5], or average about 22-24 days[17]. Newby[22] found that larval feeding was maximized at 35°C, but fell off rapidly if temperatures increased any higher. Similarly, Tomberlin *et al*[21] reported that increasing the temperature from 27 to 30°C reduced larval development time by 1.5 days. However, at 36°C larval development time actually increased slightly. More importantly, survival from larvae to adult was 83-92% at 27°C and 74-97% at 30°C. In contrast, virtually no adults emerged from pupae formed at 36°C, adult survival being less than 1%.

Although larvae will successfully mature when held in laboratory conditions at 22°C, the larval development stage can last up to 2 months or even more. As temperature drops further, larvae stop feeding at 15°C, becoming completely inactive at 10°C. BSF larvae can withstand 0°C for only a few hours[22].

Humidity is also important. Both egg hatch and adult emergence are maximized at 70%RH or more and greatly reduced if humidity is 50% or less[23]. This is important if colonies are being kept in a heated greenhouse, where humidity can fall quite low. Under these conditions a humidifier should be used.

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[19] Sheppard DC et al. 2002. Rearing methods for the black soldier fly (Diptera:Stratiomyidae). J. Medical Ento. 39:695-698.

[20] Sheppard DC, Newton GL, Thompson SA. 1994. A value added manure management system using the black soldier fly. Bioresource Technol. 50:275-279.

[21] Tomberlin JK, Adler PH, Myers HM. 2009. Development of black soldier fly (Diptera:Stratiomyidae) in relation to temperature. Environ. Entomol. 38:930-934.

[22] Newby R. 1997. Use of soldier fly larvae in organic waste management. In Proceedings of the 'Compost 97' Conference, 14–15 July 1997, Brisbane, Australia

[23] Holmes LA VanLaerhoven SL Tomberlin JK. 2012. Relative humidity effects on the life history of *Hermetia illucens* (Diptera: Stratiomyidae). Environmental Entomology. 41:971-978.

5.6 Larvae – diet

BSF larvae are voracious feeders and will consume an incredible range of organic materials. Much of the research on these insects has focused on their ability to consume animal and human wastes. They are particularly associated with poultry manure.

5.6.1 Organic wastes

Before the advent of closed sheds, the space underneath poultry layer houses would become naturally heavily infested with BSF larvae, which reduced the volume of the waste by at least half[16]. In addition to reducing the need to dispose of poultry manure, the insect can provide the additional benefit of outcompeting housefly larvae, which are otherwise major pests[20].

Various studies have reported that larvae can successfully develop in poultry and swine manure, sewerage sludge and liquid leachate from compost[24]. They can even live in dead human bodies; black soldier fly larvae have been used to estimate postmortem intervals for human corpses[25].

Not all organic materials provide a suitable diet for BSF. Newby[22] noted that BSF populations in compost bins tended to disappear if large amounts of putrescible wastes (such as meat scraps), grass clippings or sawdust were added. Although BSF larvae fed entirely on liver or fish renderings grow rapidly, mortality is extremely high. Combined mortality from pupal, pre-pupal and adult stages was 99.8% and 98.2% for larvae fed fish or liver respectively[14]. Meat meal is similarly considered unsuitable for rearing BSF[13].

5.6.2 Vegetable wastes

While plant materials are a natural food for BSF, the larvae cannot easily survive on organic materials such as plant stems, grasses and mature leaves. It seems likely that the larvae are unable to effectively digest lignin[26], which is a key component of plant cell walls and highly resistant to biodegradation. This may explain why cow manure is far less suitable for BSF than poultry or pig manure[27]; whereas pig manure contains only about 2% lignin, cow manure can be 10% lignin and wheat straw is about 23% lignin.

The suitability of vegetable wastes for BSF production is therefore likely to relate to their lignin content. Fortunately, lignin is extremely low in most vegetable crops, being below 0.4g/100g (fresh weight) in products such as beans, peas and spinach[28]. Where lignin is present it tends to be concentrated in the skin. This means a waste product such as dry tomato pomace is 11% lignin.

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[24] Popa R Green TR. 2012. Using black soldier fly for processing organic leachates. J Econ Entomol. 105:374-378.

[25] Pujol-Luz JR et al. 2008. The black soldier fly, *Hermetia illucens* (Diptera, Stratiomyidae), used to estimate the postmortem interval in a case in Amapa State, Brazil. J. Forensic Sci. 53:476-478.

[26] LongYu et al. 2012. Biodiesel production from rice straw and restaurant waste employing black soldier fly assisted by microbes. Energy. 47:225-229.

[27] St-Hilaire S et al. 2007. Fish offal recycling by the black soldier fly produces a foodstuff high in Omega-3 fatty acids. J. World Aquaculture Soc. 38:309-314.

[28] Herranz J et al. 1983. Cellulose, hemicellulose and lignin content of raw and cooked processed vegetables. J. Food Sci. 48:274-275.

Although no studies have tested feeding specific vegetables for BSF, several studies have used unspecified "fruit and vegetable" waste streams. These have reported excellent development rates and low mortality on such diets.

5.7 Effect of diet on development

Although BSF larvae can survive and grow on many different products, development time, feed conversion efficiency, mortality, pupal weight, fat content and protein content are strongly affected by what they have consumed (Figure 7).

For example, including 10% fish offal in the diet of BSF larvae increased their lipid content by 43%, approximately 3% of which comprised omega-3 fatty acids. Changes could be seen with as little as 24 hours feeding, and would substantially increase the value of the end product for aquaculture[27]. Similarly, increasing the fat content in a standard diet increased the percentage dry weight of pre-pupae from 36 to 40%[29].

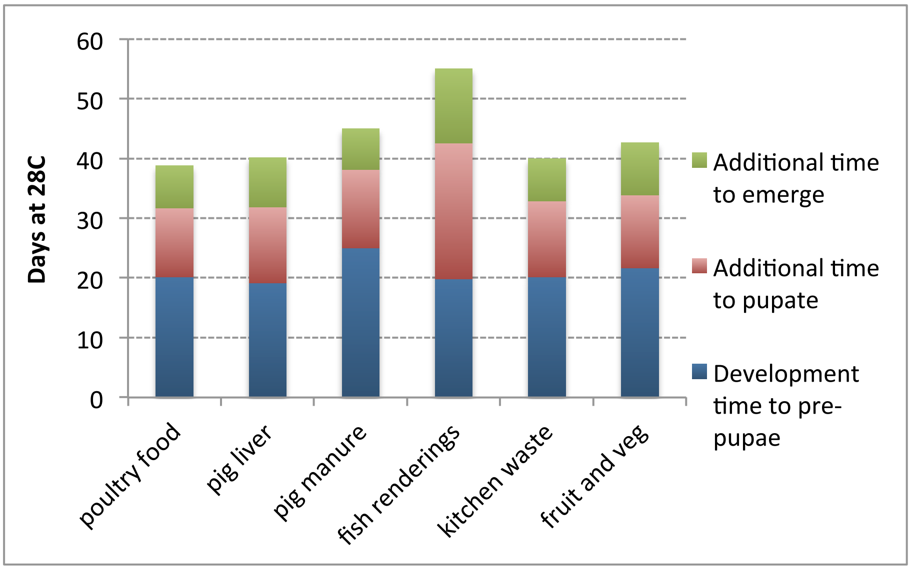

Figure 7 - effect of food type on development times of BSF. Adapted from Nguyen et al., 2013.

Nguyen[14] compared development rate, size and mortality of BSF fed on poultry feed, pig liver, pig manure, fish renderings, kitchen waste, or mixed fruit and vegetable waste. Larvae that fed on vegetable waste had a slower growth rate than those fed kitchen waste; this is likely due to there being fewer available calories in the former.

Taking into consideration mortality during development to the pre-pupa stage, the highest total yield from the food provided was from larvae fed poultry feed, followed by those fed fruit and vegetable waste or pig manure (Figure 8). Unfortunately total feed consumed during development was not reported. However, it is notable that poultry feed and pig manure contained 322 and 129 KJ/100g respectively while kitchen waste contained 583 KJ/100g. In contrast, the fruit and vegetable wastes used only contained 68 KJ/100g. If feed

[29] Barry T 2004. Evaluation of the economic, social and biological feasibility of bioconverting food wastes with black soldier fly (*Hermetia illucens*) PhD Thesis University of Nth Texas.

supply was at all limited, this could explain why fruit and vegetable wastes did not perform better.

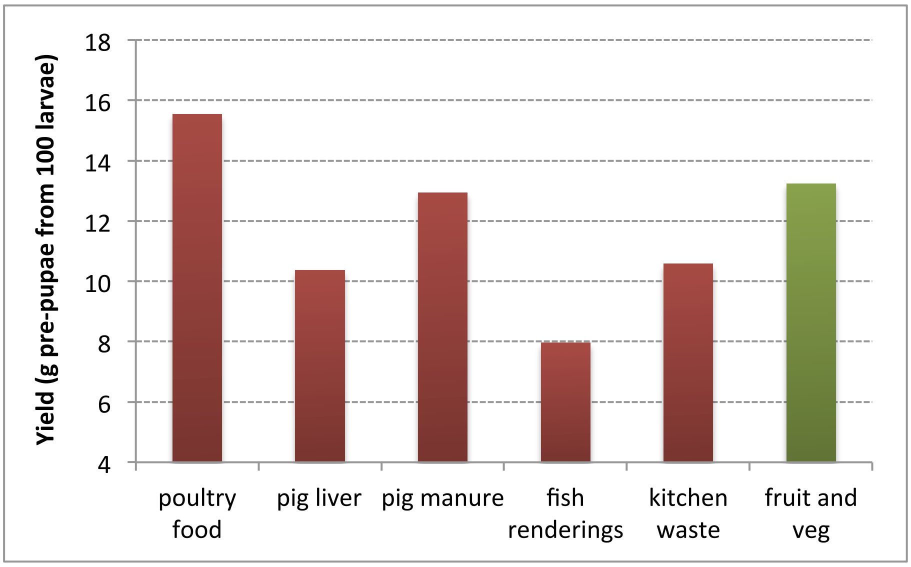

Figure 8 - Total yield in grams of prepupae from an initial stock of 100 larvae, calculated from average pre-pupal weight and taking into account percentage mortality during development. Derived from Nguyen et al., 2013.

Kalova and Borkovcova[30] fed BSF larvae 14 different waste types over a 14-day period. Only four waste streams resulted in adult flies during this period – mixed fruit and vegetables, catering and municipal wastes, suggesting that these diets were the most suited to larval development.

[30] Kalova M Borkovcova M. 2013. Voracious larvae *Hermetia illucens* and treatment of selected types of biodegradable waste. ActaIniv. Agric. et Silvic. Mendelianae Brunensis 9:77-82

5.8 Feed conversion efficiency

Estimates of feed conversion into pre-pupal biomass vary greatly, ranging from only 6–10%, to 12-15% and even up to 24%. This wide range may be due to the large number of factors potentially affecting feed conversion rates. In addition to feed quality, these include population density, presence of symbionts and environmental conditions[31].

Kalova and Borkovcova[32] present some data on feed consumed and pre-pupae produced from vegetable wastes. Unfortunately initial numbers of larvae were only estimated and neither mortality nor total yield was reported. However, given an average weight of 150mg/larvae, the data presented suggest that 6,653g of fresh waste produced only about 18g larvae. Even if the waste was only 10% dry matter, this appears a surprisingly low feed conversion rate; 665g feed DW produced 9g larvae DW, giving a feed conversion of less than 2%. However, given the lack of supporting detail in this study, this would seem a dubious conclusion.

Feeding rate may have a large effect on feed use efficiency. Diener *et al*[10] found that the optimal feeding rate was 100mg poultry food.day^{-1}.larvae^{-1}. This maximised the trade-off between reducing the volume of waste material and increasing production of pre-pupae. At this feeding rate 9.6% of food was converted into biomass (pre-pupal dry weight). Nearly 30% of the feed was used in metabolic activity with 60.7% remaining as uneaten material and waste. This means that 1kg (dry weight) of poultry feed (or a similar volume of vegetable waste) can produce 96g pre-pupae (dry weight), a feed conversion ratio of 10.4:1. Similar results were reported by Barry[29], who found that 9.1% of a dog-food diet was converted to harvestable pre-pupae biomass.

However, higher rates may be possible with more efficient systems. According to Newton *et al*.[33] pilot scale production systems using pig manure have found dry matter feed conversion rates of 12-15%, while rates as high as 24% have been achieved in small laboratory assays. The authors suggest that similar rates should be possible in a refined production system.

Certainly, production methods are still relatively crude and large improvements may be possible. Large differences in size and vigour exist between wild populations[34], suggesting that simply selecting appropriate strains for mass production could have major benefits.

The addition of symbionts could also provide benefits. For example, the standard diets often used to maintain BSF colonies are well moistened layer hen food, generally containing about 15% protein, or the Gainsville housefly diet[35], which is nutritionally similar. However, it has been observed that larvae and adults reared on these diets are smaller and shorter lived than wild-caught specimens[17]. This may be due to the lack of symbiotic gut bacteria, which

[31] Scriber JM Slansky F Jr. 1981. The nutritional ecology of immature insects. Ann. Rev. Entomol. 26:183-211.

[32] Kalova M Borkovcova M. 2013. Voracious larvae *Hermetia illucens* and treatment of selected types of biodegradable waste. ActaIniv. Agric. et Silvic. Mendelianae Brunensis 9:77-82

[33] Newton GL Sheppard DC Burtle GJ. 2008. Black soldier fly prepupae – a compelling alternative to fish meal and fish oil. Animal manure and waste utilization conference, Research Brief.

[34] Fen Zhou et al. 2013. Developmental and waste reduction plasticity of three black soldier fly strains (Diptera: Stratiomyidae) raised on different livestock manures. J. Med. Entomol. 50:1224-1230.

[35] Hogsette JA. 1985. New diets for production of house flies (Diptera: Muscidae) in the laboratory. J. Econ. Entomol. 85:2291-2294.

have been demonstrated to increase feeding efficiency of larvae[36]. Similar results have been found with island fly (*Dirioxa pornia*), which cannot be raised in the laboratory without the addition of certain bacteria to the food source (P Crisp, pers. com.).

Adjusting the harvest method could further help maximize yield. Published results suggest that significant weight loss occurs in the last few days as larvae stop feeding and develop into wandering pre-pupae. Diener *et al*[10] reported that fifth instar larvae reached an average of 100mg dry weight, whereas the average weight of the pre-pupae was 48mg; half the larval weight appears to have been lost to metabolic activity during this last phase of maturation. Similarly, Tomberlin *et al*.[17] reported final larval weights of 150−170g compared to pre-pupae weights of 100−110g.

Minimising the final phase of development before harvest would therefore greatly increase total yield, potentially almost doubling productivity per kg food supply. As most research has focused on waste reduction rather than biomass production, no information could be found on finding ways to achieve this. However, it seems possible that removing food, adding water or other treatments could help stimulate larvae to leave the media, increasing efficiency of collection.

5.9 Processing

BSF larvae and pre-pupae are suitable for feeding a range of domestic animals. Various studies have shown them to be suitable for pigs[37] and poultry[38] and they are promoted as an ideal food for pet reptiles. However, it is aquaculture feed that offers the most promise as well as greatest potential return on investment.

Initial research has been conducted using BSF meal as a partial or full substitute for fish meal in aquaculture diets. While many papers have reported good performance, others have found some slight decrease in growth rate. There is a clear need for more research on optimising quality of the larvae as well as the processing method used[39]. One advantage of BSF is that their dry matter content is relatively high – about 44% − compared to fishmeal, which may be about 25%. This should make drying and processing easier and cheaper.

It has been previously noted in this review that supplementing larval food with fish renderings or algae can increase their omega-3 content[27 40], making them more suitable replacements for fishmeal. Total fat content is also strongly affected by diet. Reported values range from 15−21% of dry matter for larvae fed on poultry or cow manure, to 30% on a 50:50 mix of cow manure and fish offal[27] to 42−49% when larvae are fed on oil rich food waste. This is far higher than fishmeal, which only contains 8−11% fat.

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[36] GuoHui Y et al. 2011. Inoculating poultry manure with companion bacteria influences growth and development of black soldier fly (Diptera: Stratiomyidae) larvae. Environ. Entomol. 40:30-35.
[37] Newton GL et al. 1977. Dried Hermetia illucens larvae meal as a supplement for swine. J. Anim. Sci. 44:395-400.
[38] Hale OM. 1973. Dried Hermetia illucens larvae (Diptera: Stratiomyidae) as a feed additive for poultry. J. Georgia Entomol. Soc. 8:16-20.
[39] Tran G et al. 2014. Black soldier fly larvae (*Hermetia illucens*). Feedipedia.org. updated 7/1/2014.
[40] Sealey WM et al. 2011. Sensory analysis of rainbow trout, *Oncorhynchus mykiss*, fed enriched black soldier fly prepupae, *Hermetia illucens*. J. World Aquaculture Soc. 42:34-42.

Another potential issue with BSF is that the outer skin contains chitin. Some fish, such as tilapia and turbot, are unable to easily digest chitin, so feeds containing this can reduce growth[41 42]. Chitin is also a component of shellfish, so it could be expected that fish that naturally eat shrimp or crabs (or insects) would be able to process this compound. However, even among these species, lack of exposure during early development may mean the enzymes required are no long present and growth is reduced[42].

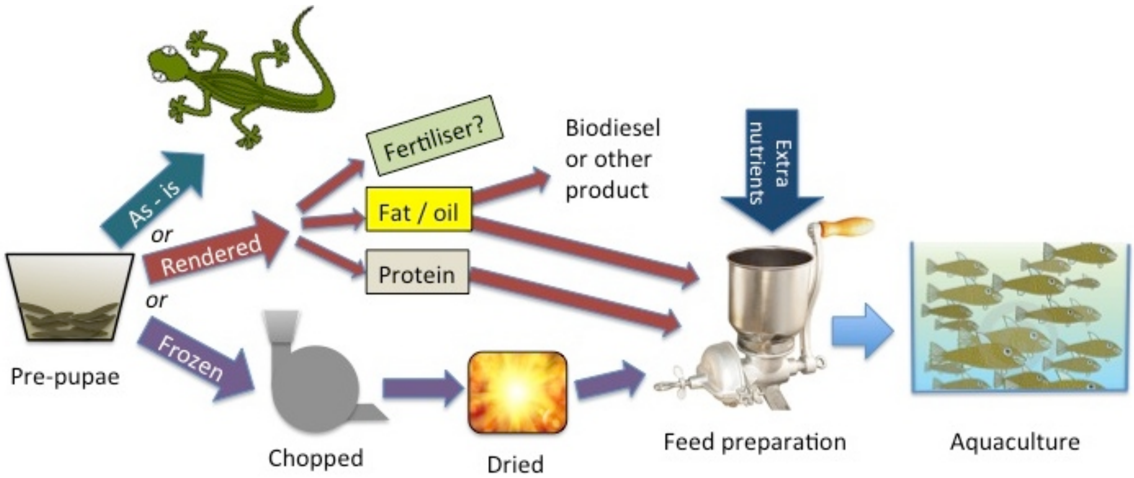

Figure 9 - Processing options for BSF prepupae

These issues may be overcome through processing (Figure 9). Several options exist for handling the harvested pre-pupae. Initial studies simply used the harvested pre-pupae as they were – alive or dead, whole or chopped. However this is only suitable for larger fish or reptiles. More commonly the BSF larvae are frozen, dried and ground into meal. Recent studies have mixed a meal with other ingredients in a pelletised form. If fat content needs to be reduced the frozen pupae can be cut before processing, allowing some of the intercellular fat to leak out[42]. This fat can then be used for other purposes, such as biodiesel production[26].

A third option is to render the pupae (heating under pressure) to separate the protein, fat, chitin and other materials. Rendering allows these elements to be recombined in proportions optimised for a particular use.

For example, fishmeal is usually 60% protein or more, whereas BSF dry matter generally ranges from 40–44% protein[39]. For this reason, a diet of BSF alone is inadequate for most fish species[43]. BSF also contain more fat than fishmeal, and relatively high levels of dietary fibre. Nutritional data comparing BSF to fishmeal is presented in Appendix 1 of this report.

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[41] Shiau SY, Yu YP. 1999. Dietary supplementation of chitin and chitosan depresses growth in tilapia, *Orechromis niloticus x O. aureus*. Aquaculture 179:439-446.

[42] Kroeckel S et al. 2012. When a turbot catches a fly: evaluation of a prepupae meal of the black soldier fly (*Hermetia illucens*) as fish meal substitute – growth performance and chitin degradation in juvenile turbot (*Psetta maxima*). Aquaculture 364:345-352.

[43] Bondari K, Sheppard DC. 1987. Soldier fly, *Hermetia illucens* L. larvae as feed for channel catfish, *Ictalurus punctatus* (Rafinesque), and blue tilapia, *(Oreochromis aureus* (Steindachner). Aquaculture Fisheries Mgmnt. 18:209-220.

5.10 Use in aquaculture

To date, the results of feeding trials have been mixed. In many cases there is a direct relationship between the amount of feed a fish consumes and its weight gain, with the feed formulation itself having less of an effect. Although fish will eat a food and can survive on it well, if it is not palatable or easily digested then growth rates are likely to be reduced.

Various studies have found BSF to be both suitable and unsuitable for blue tilapia; suitable for prawns; suitable to some extent for channel catfish; and suitable for rainbow trout only if larvae are fed an augmented diet. Results of published studies are presented in Table 1.

Table 1 - Summary of published feeding trials with BSF

Species	BSF feedstock and preparation	Result	Fit?	Reference
Blue tilapia	Hen manure, dried and chopped	Diets containing 50, 75 and 100% BSF suitable for tilapia over 10 weeks' feeding. Fish quality acceptable to consumers	Y	Bondari & Sheppard 1981
Blue tilapia	Hen manure, dried	Fish ate food but weight gain reduced when fish fed whole or chopped BSF compared to commercial feed	N	Bondari & Sheppard 1987
Channel catfish	Hen manure, dried	Weight gain reduced when 10% fishmeal replaced with BSF meal. Fish did not grow if fed 100% BSF.	N	Bondari & Sheppard 1987
Prawns	Dried distillers grain	Similar performance from BSF-based feed compared to commercial product, feed cost reduced	Y	Tiu, 2012
Rainbow trout	Cattle manure	Diet containing 25% or 50% BSF reduced palatability to fish, growth reduced	N	Sealey *et al* 2011
	Cattle manure enriched with up to 50% fish offal	Growth same as control with diet containing 25 or 50% BSF	Y	
Rainbow trout	Pig manure	Replacing 25% of fishmeal with BSF did not affect weight gain or feed conversion	Y	St Hilaire *et al,* 2007
Turbot	Dried, defatted, ground into meal	Replacing 0-75% of fishmeal in the diet of turbot reduced final weight. Weight gain was proportional to the amount of fishmeal in the diet. Negative result likely due to indigestibility of chitin	N	Kroeckel *et al,* 2012

It seems likely that removing/reducing chitin is a key step needed to increase digestibility of BSF meal. This would also effectively increase its protein content and generate another product with potential value[33]. It may also be possible to manipulate pupal maturity at harvest in order to reduce chitin content; immature larvae are likely to have lower chitin content than pre-pupae, while recently moulted larvae may have less again. As previously noted, harvesting immediately before the pre-pupal stage could have the additional benefit of maximising yield[10]. Techniques have been developed for housefly larvae to separate them from the feed medium – these include exposure to light and flotation[44]. Similar techniques have not been developed for BSF due to their convenient, self-harvesting behavior. However, early harvesting could potentially result in a superior quality product.

Manipulation of feed source could be another way to improve suitability for aquaculture. The promising results reported by Sealey *et al*[40] from augmenting larval diet with fish offal demonstrate the importance of managing diet. No studies have reported on the palatability or nutritional quality of BSF fed on vegetable waste, or on vegetable waste augmented with fish waste, algae or other source of fatty acids. This therefore remains an area for more research.

5.11 Commercial production

Worldwide, this review has identified three companies producing BSF on a true commercial scale. There are numerous other 'backyard' producers who supply enthusiasts, pet owners and their own domestic animals.

In addition, it seems highly probable that semi-commercial production has been trialed in Indonesia and other less developed nations – photographs posted on BSF-related websites would indicate this, although no other information is provided. Certainly some of the methods would seem well adapted for use at the village level. Rearing BSF could both help dispose of waste (often a serious issue in less developed regions) and provide protein in diets that may otherwise be protein-deficient. In many such countries insects are a normal part of the diet and therefore both suitable and acceptable for human consumption.

EnviroFlight – Yellow Springs, Ohio USA

EnviroFlight was founded in 2009 by Glen Courtright. Glen came from the biofuel industry, where he was involved in ethanol production. However, he felt that producing food was a higher priority with greater growth potential. Moreover, he was familiar with the large quantities of DDGS – Dried Distillers Grain with Solubles – that is produced as a byproduct of ethanol production, as well as by distillers and brewers. DDGS is corn and grain from which much of the starch has been extracted, but which still retains high levels of protein, fibre and oils (Figure 10).

It took three years of research and development before the company successfully achieved commercial production of BSF in 2012. Flies are maintained at 30^{o}C with between 30-50% RH for different parts of the process. The company has developed a (patented) system for encouraging mating. Adult flies are enclosed in tall, cylindrical wire cages inside a heated, humidified glasshouse (Figure 10). Lidded plastic containers with oviposition attractant are at the bottom of each cage. As part of the process the company plays music to the flies (Barry White, apparently!), which has generated substantial publicity in itself.

[44] El Boushy AR Klaasen GJ Kelelaars EH. 1985. Biological conversion of poultry and animal waste to a feedstuff for poultry. World Poultry Sci. 41:133-145.

Figure 10 - The Enviroflight facility, showing larvae in DDGS, Glen Courtright with the raising trays, and inside the rearing facility and the cages designed for mating and oviposition of adult flies.

Much of the initial production has been sold to zoos and pet owners for feeding to animals as diverse as armadillos, sun bears, birds and bush babies. However, the business is expanding and aquaculture feeds are the clear long-term target. Processing involves rendering the larvae to extract the oil, boosting protein content to more than 70% DW. While testing is still being conducted in tanks located at the facility, the company suggests that their product will be a suitable feed ingredient for rainbow trout, yellow perch, bass and bluegill. It is unclear whether production is already used for this purpose.

Moreover, the company states that the frass remaining after larval feeding is suitable for a number of omnivorous aquaculture species such as tilapia, freshwater prawns and catfish. It already sells sinking pellets designed for freshwater prawns, an expanding market. The frass is also sold as soil amendment / fertiliser, having a N:P:K ratio of 5:3:2, high in chitin and beneficial bacteria.

Glen Courtright has advised that vegetables would also be suitable for using in their BSF production system. They could easily be incorporated into the feeding slurry, which is formulated to contain 50-60% moisture and less than 15% fat. The system is modular, so the company is able to build systems for breeding, incubation and bioconversion as required. They also supply ancillary equipment such as dryers, presses and hammermills for pelletisation. While Glen has advised that they are just starting to supply hardware to licensees of their technology, he was unable to provide any guide as to costs without knowing more about the type and quantity of material to p=be processed, the climate and other factors.

Organic Value Recovery Solutions - Georgia USA

This company was founded by Dr Craig Sheppard, the researcher who pioneered black soldier fly production, in partnership with his long-term co-researcher Dr Larry Newton. The Organic Value Recovery System process is designed to convert waste streams including food waste, manufacturing residuals, manures, brewers grains and other organic wastes to BSF meal. Vegetable wastes are included in this, although no specific information is given and no results with vegetable wastes are provided.

A small-scale factory has been developed. It appears that the major supply is currently to herpetology enthusiasts (through the partnered company "The Phoenix Worm store"). However this is a sideline to the major interest in aquaculture feeds and use of the method to dispose of wastes – particularly from intensive pig production.

It is claimed that it is possible to replace 25-30% of the fishmeal in salmon diets with milled BSF prepupae, although the company notes that higher percentage replacement would be possible if chitin is removed. It is also stated that channel catfish can be produced solely using BSF meal.

The Company estimates feed conversion efficiency at around 25%. That is, for every 4kg DW feed 1kg DW larvae can be produced. They estimate the value of this product at $1,500-$2,000/tonne raw protein (approximately $660-$880/t DW). The "phoenix worms" sold to enthusiasts retail for $39/1,000 larvae (approximately 160g). It is also noted that the frass makes a useful soil amendment. This is sold for $4 per 50lb.

The primary business of this company appears to be developing BSF production for companies with waste issues, rather than producing BSF itself. The major clients are intensive animal feeding operations. For example, they are currently involved in setting up a 100 ton processing facility for pig manure in South Africa. The facility itself is expected to be 10m x 60m, depending on the mating success percentages of the local BSF strain used.

The AHR research team enquired about the feasibility of setting up a similar facility for vegetable wastes in Australia. The company has suggested that the best way forward is to conduct an initial feeding trial with the feedstock we had in mind. This would provide information on feed conversion rates and therefore the size of facility needed and the financial viability of the operation – which is exactly what has been proposed as the next stage of this project.

Hermetia Futtermittel – Baruth/Mark, Germany

Scant information is available about this company, and it is mostly in German. It comprises three separate entities;

1. Hermetia Futtermittel GbR (Hermetia feed): Research and Development
2. Hermetia Baruth GmbH : First production site
3. Hermetia Deutschland GmbH & Co KG : Marketing, sales and management

The technology on which the company is based comes from a 2005 feasibility study by SA Katz "Development of alternative protein sources for fish meal for trout feed", funded by the German Institute for Nutrition and Agriculture. This ran successful feeding experiments with trout and BSF. Since then, BSF cultures have been maintained at Katz Biotech and Hermetia Futtermittel.

The report on a subsequent commercialisation project is available online in German. The following may be summarised from the English translation;

- A process has been developed to allow harvesting at a defined time, rather than by waiting for natural migration from the substrate
- Larvae are currently killed by freezing, but it is hoped to develop a method to kill with hot water; research is needed as this method has to be effective without damaging any of the larval proteins.
- The fat content of the larvae was too high for easy processing into pellets. A press has therefore been developed to mechanically separate protein from fat.
- Skretting, Norway (world's largest fish feed producer) conducted a trial with Atlantic salmon using 50kg of defatted, 74% protein BSF meal. The resulting data was not divulged by Skretting. However, it was reported that the fish took the feed well, even though the protein digestibility coefficient was 67% compared to fishmeal at 90%.
- The Department of Feed Inspection Service has determined that hydrolysed BSF meal is not subject to BSE / TSE Regulation so can therefore be marketed as animal food.

It is known that Hermetia Futtermittel uses agricultural wastes, although the nature of these wastes is not clear. Substrates used to rear pupae are not recorded in the report. However, it is stated that the production process has been optimised and different materials have been evaluated. A number of patents have been lodged as a result of the project.

Enterra Feed – Vancouver, Canada

Enterra was founded by Entrepreneur Brad Marchant and well known geneticist and environmentalist David Suzuki. The company grows black soldier fly larvae on what they describe as a fixed recipe comprising pre-consumer food wastes of vegetables, fruit, grains and fish. The company offers a service whereby they will collect certain kinds of food processing and grocery store waste.

The larvae are grown in an indoors heated environment and used to produce 3 main products – Grubbinz (whole dried larvae), feed meal which is a processed meal derived from the larvae which contains 55-60% protein and 15-17% fat, and extracted oil. Fact Sheets on these products are included in Appendix 2 of this report. It is interesting to note that 'Grubbinz' are recommended for feeding to poultry, tilapia and catfish, but as no more than 30% of the diet by dry matter.

Although the (patent pending) process to grow the larvae has been developing since 2007, the Company appears to have only begun commercial supply in October 2013. They have undoubtedly gained extensive publicity due to their connection with David Suzuki.

6 Yellow Mealworm - *Tenebrio molitor*

6.1 Key points

Advantages

- Easy to breed
- Females lay large numbers of eggs directly into feedstock
- Flexible food sources can be used
- Already widely produced commercially
- Extremely efficient converters of feed to biomass

Disadvantages

- Use in aquaculture is little researched
- Chitin content may make it unpalatable to some fish species
- Difficult to separate larvae from feeding material
- Cannot be reared on vegetable waste alone – low cost source of grains also required
- Vulnerable to excess moisture

6.2 Natural distribution

Mealworms have been known for centuries, partly because of their destructiveness as pests of stored grains and flour, but also because of their usefulness as food for small animals such as birds, fish and reptiles. Initially named by Linnaeus in 1758, their biology was described as early as 1883, with a more detailed account from Cotton in 1927[45].

There are two species of mealworm – the common *Tenebrio molitor* and the smaller and rarer *T. obscurus*. Mealworms are the larval forms of two species of darkling beetles. Originally from Europe, mealworms are now found in temperate regions around the world. They are easy to breed and are already produced industrially in many countries.

6.3 Lifecycle and morphology

The natural lifecycle of mealworms results in one generation per year, or only one every two years under cool conditions. The insects would normally overwinter as larvae, then pupate and emerge as adult beetles in spring. However, in culture, larvae can complete the transition from egg to adult in 3−4 months. Maturation involves passing through a variable number of instars ranging from 8 to 22. Mature larvae are up to 32mm long, weigh about 120−150mg and are a light yellowish brown colour with darker stripes (Figure 11). Some

[45] Cotton RT 1927. Notes on the biology of the meal worms *Tenebrio molitor* L. and *T. obscurus* Fab. Annals Entomol. Soc. America 20:81-87.

commercial suppliers treat larvae with juvenile hormone to prevent maturation into adult beetles, resulting in giant mealworms weighing more than 300mg[46].

Figure 11 - Mealworms, mature larvae and pupae (A Wild) and adult beetle (USDA-ARS-GMPRC)

Pupae are simply formed within the substrate. These are initially creamy, but darken as they develop. The glossy black adult beetles then emerge after 2–3 weeks. They can live for 2–3 months, feeding on the same substrate as the larvae. A culture of mealworms may therefore contain all lifestages at the same time. Adults rarely fly; unless they need to find food they simply walk everywhere.

6.4 Mating and oviposition

Mating occurs a few days after emergence. No special conditions are needed, and the fertilised female can then continue to oviposit throughout her adult life. A female beetle will typically lay 120–180 eggs during a 2–3 week period. The white, oval eggs are laid singly or in small clusters in flour or meal. They are initially sticky, causing them to become covered with particles of food. Incubation time is a factor of temperature, and may be as little as 4 days or up to nearly 3 weeks[45].

6.5 Larvae – diet and environment

Mealworms are omnivores, and can eat a wide range of different plant and animal materials. These include fruit, vegetables, meat and even feathers[47]. The basic substrate typically used for mealworm larvae is a grain product such as oats, flour or wheat bran. To this is added a protein source such as yeast, soy bean flour or skimmed milk powder[48]. An ideal feedstock needs to contain about 20% protein on a dry matter basis[47].

Relative humidity has a major effect on growth rates. At 25°C, increasing humidity from 30% RH to 70% RH triples growth rate. However, if RH continues to increase mould becomes a problem and larval feeding slows[49].

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[46] Finke MD. 2002. Complete nutrient composition of commercially raised invertebrates used as food for insectivores. Zoo Biology 21:269-285.

[47] Ramos-Elorduy J et al. 2002. Use of *Tenebrio molitor* (Coleoptera: Tenebrionidae) to recycle organic wastes and as feed for broiler chickens. J Econ. Entomol. 95:214-220.

[48] Aguilar-Miranda E et al. 2002. Characteristics of maize flour tortilla supplemented with ground *Tenebrio molitor* larvae. J. Agric. Food Chem. 50:192-195.

[49] Martin RD et al. 1967. Culturing mealworms as food for animals in captivity. Principles Zoo Animal Feeding 63-70.

While vegetables are added to provide moisture and additional nutrients, it is also important that the mix does not get too wet. This can lead to fungal pathogens attacking the larvae, and in some cases colony collapse. While larvae are strongly attracted to fresh produce, the colony must be monitored closely to ensure the area does not become wet and mouldy. For this reason some producers recommend against including vegetables with a high moisture content, instead preferring products such as carrot or pumpkin.

6.6 Feed conversion efficiency

One advantage of mealworms often suggested as a major benefit is that they are extremely efficient converters of feed to biomass. A study by Spang[50] demonstrated that feed conversion was highest during early development but then decreases considerably. This result shows that it would be more efficient to harvest larvae early, before their feed use efficiency drops, in order to maximize returns on the feed. Similar results have been reported for cattle. Despite this, mealworms proved extremely efficient converters of feed into biomass. The mean efficiency of conversion of ingested food by mealworms was 0.33. That is, 3kg feed (DW) could produce 1kg (DW) of mealworms. For comparison, ECI values for whole cattle (not all of which is edible) range from 0.12 – 0.16.

The high moisture content of fresh vegetables (80-90%) needs to be considered in these calculations. For example, despite estimating feed conversion at an extremely high 0.45 (FW), Oonincx *et al*. estimated that 260t fresh carrots combined with 182t mixed grains would be needed to produce 83t of mealworms. While the value of the insect meal produced by this process is not known, if it is assumed to be valued at $1,500-$2,000/t raw protein, this would represent a return of approximately $124/t carrots, less the cost of grain and other inputs[55].

6.7 Processing and use

Mealworms are often fed live to birds, reptiles and even fish. Commercial products also include dried and canned products. However, processing into aquaculture diets requires larvae to be dried and ground. Feeding studies have used drying times that vary from 2−3 days in the sun to oven drying for 200 minutes[51]. The effect of these differing methods on nutritional composition has not been studied.

Surprisingly, given their long history of feeding to different species, there is little research on the use of mealworms as commercial feed. They have been found suitable for poultry and laying hens[52], although methionine needs to be added[47]. The larvae may also need to have their diet fortified with extra calcium in order to contain sufficient calcium for growing chicks[53].

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[50] Spang B. 2013. Insects as food: Assessing the food conversion efficiency of the mealworm (*Tenebrio molitor*). MSC Thesis submitted to Evergreen State College USA.
[51] Tran G et al. 2013. Mealworm (*Tenebrio molitor*) Feedipedia.org, a program by INRA, CIRAD, AFZ and FAO. Updated 30/11/2013.
[52] Giannone M. 2003. A natural supplement made of insect larvae. Rivista di Avicoltura. 72:38-41.
[53] Klasing KC et al. 2000. Increasing the calcium content of mealworms (*Tenebrio molitor*) to improve their nutritional value for bone mineralization of growing chicks. J. Zoo Wildlife Med. 31:512-517.

Only one published study has examined the use of mealworms for aquaculture. This found that replacing up to 40% of the diet of African catfish with mealworm meal did not significantly affect growth or feed utilisation efficiency. Substituting more than this of the diet significantly reduced yield[54].

One area of increasing research is the use of mealworms as part of the human diet. It has been proposed that mealworms could help meet growing international demand for animal proteins in the human diet. Supply of protein by mealworms would require similar energy inputs to other meats, but would require far less land and have significantly less global warming potential overall[55]. It has even been suggested that mealworms would be an ideal candidate for animal protein production during space travel, as it could recycle inedible plant parts remaining after vegetable production[56].

The economics of such activities are not known. Although already in commercial production, profitability relies on the high prices paid through the pet trade rather than commercial feedstock. The potential of this market is limited.

The composition of mealworms is shown in the Appendix of this report.

[54] Ng WK. 2001. Potential of mealworm (*Tenebrio molitor*) as an alternative protein source in practical diets for African catfish, *Clarius gariepinus*. Aquaculture Research 32:273-280.
[55] Oonincx DGAB and de Boer IJM. 2002. Environmental impact of the production of mealworms as a protein source for humans – a life cycle assessment. PLOS One 7:12 e51145.
[56] LeYuan L et al. 2012. Feasibility of feeding yellow mealworm (*Tenebrio molitor L.*) in bioregenerative life-support systems as a source of animal protein for humans. Acta Astronautica 2012.03.012

7 Superworm - *Zophobas morio*

7.1 Key points

Advantages

- Large size makes handling easier
- Easy to rear and will eat range of vegetables

Disadvantages

- Needs individual handling to enable pupation and rearing to adult
- Cannot be reared on vegetables alone
- Requires heating for maximum productivity
- High levels of chitin likely to reduce palatability for many aquaculture species
- Little or no data on suitability for commercial animal or aquaculture feed
- Although there are large numbers of small producers supplying the pet feed market, there are no major commercial producers of this insect

7.2 Natural distribution

Also referred to as “giant mealworm” or “morio worm”, the superworm looks similar to a mealworm but is much larger, reaching up to 6cm long. Like mealworms, superworms belong to the darkling beetle family of ground dwelling beetles. Despite these similarities, the two species are not that closely related.

Superworms are more of a tropical species, originating in Central and South America where they live in rotting plant debris. However, they are now found around the world, including Europe, Canada and Australia, mainly due to their popularity as a feed for larger reptiles, birds and chickens[57].

7.3 Lifecycle and morphology

Superworms can pass through a complete lifecycle in around 6 months although, as with mealworms, this is highly temperature dependent. As a warm climate animal, they do not tolerate low temperatures – mealworms are commonly stored in the refrigerator before use, but this will kill a superworm. They are also relatively fast moving and active. The ideal temperature for development is around 30°C, although they will happily tolerate up to 35°C[58] and the standard insect rearing conditions of 26-28°C are also suitable[59].

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[57] Abd Rahman Jabir MD et al. 2011. Effects of amino acid supplementation in superworm based diets on growth performance and feed utilization of juvenile Nile tilapia. Int. Fish. Symp. 2011.
[58] www.reptileexpert.org/breeding-superworms. Accessed Feb 2014.
[59] Farahiyah IJ et al., 2012. Superworm larvae, *Zophobas morio*, as protein source for fish. Proc. 5th Int. Conf. Animal Nutr. Malacca, Malaysia 24th-26th April.

 

Figure 12 - Superworm larvae and adult (S. Nelson)

Unlike mealworms, superworms do not pupate in the growing medium. They will only pupate in isolation, possibly because the species can be quite cannibalistic. To rear large larvae through to adults they need to be placed in individual containers – home growers use plastic compartments such as large pill-boxes or fishing tackle boxes. Once placed in isolation the larvae will pupate within only a few days, emerging as adult beetles around 2 weeks later if kept at around 30°C.

The beetles are initially pale but darken to red then black. Adults can be returned to the main colony, where they will mate and lay eggs. Alternatively, it may be preferable to keep beetles and large larvae separate due to the risk cannibalization of eggs and small larvae. Adult beetles prefer to have some solid ground to mate and lay eggs on rather than just the feeding substrate itself – placing egg cartons on top is one suggested method[58]. The beetles are nocturnal, and there is some evidence that a dark environment encourages egg laying. Adult beetles will mate within a few days of emergence, and lay eggs within 7-14 days[60].

7.4 Larvae – diet and use

Despite its popularity as a pet food, there are very few research publications on superworms. Essentially they require a diet similar to that of mealworms – a basal substrate of grains such as oats or wheat bran, topped with fruit or vegetable scraps. Dry conditions increase cannibalism, so having sufficient moisture is important. However, damp conditions lead to mould growth and can encourage infestation by mites. Cabbage leaves, carrot, pumpkin and other relatively low moisture content vegetables are likely to be suitable food.

At maturity, superworms can weigh over 600mg of which around 42% is dry weight (DW). Superworm larvae have been found to contain 44 - 47% protein on a dry weight basis[59, 46], which is somewhat less than that in mealworms or BSF. Fat content ranges from 34% to 43% DW, likely depending on diet[61]. Their content of acid detergent fibre, which includes chitin, is similar to that of mealworms at around 6% DW[46]; even though their larger size reduces the relative contribution of the outer cuticle to total mass, the cuticle itself is somewhat thicker.

Nile tilapia fed with a diet containing 15% superworm meal grew and developed well, especially when the diet was supplemented with methionine (superworm are deficient in this compared to fishmeal)[57]. Although digestable lipids and protein in superworm meal represent only 70% and 50% of the totals respectively, nutrients were found to be sufficient

[60] www.herpshop.com.au. Accessed Feb 2014.
[61] Leung D et al. 2012. Biodiesel from *Zophobas morio* larva oil: process optimization and FAME characterization. Ind. Eng. Chem. Res. 51:1036-1040.

for red tilapia[62]. Apart from one paper describing biodiesel production[61], these are the only references found to commercial use of superworms.

[62] Abd Rahman Jabir MD et al. 2012. Chemical composition and nutrient digestibility of superworm meal in red juvenile tilapia. Pak. Vet. J. 32:489-493.

8 Black soldier fly colony establishment

8.1 Obtaining breeding stock

Three Biopods® (Protoculture LLC) were purchased to establish an initial breeding colony of black soldier fly. Biopods are designed specifically for BSF. According to the manufacturers, using the Biopod can help turn 100kg of kitchen scraps into 15-20kg of BSF larvae. Given the relatively high moisture content of most kitchen scraps (~80%) compared to the pre-pupae (~56%), this suggests a feed conversion ratio close to 2:1.

To start the process, the manufacturers suggest simply filling the Biopod with some vegetable scraps and placing it in a shady area under warm conditions. This will attract female BSF if they are present in the environment. The presence of larvae attracts other females, who also lay eggs, establishing the colony.

Figure 13 - The Biopod unit designed for keeping BSF, aimed at home gardeners.

One of the Biopods was therefore loaded with kitchen scraps and ground coffee and placed outside, in Sydney, during December 2013. Within two weeks larvae were visible. These were divided between the other units, also placed outside. It was quickly apparent that, at this time of year in Sydney, the colonies were self replenishing. New larvae appeared regularly and pre-pupae self harvested into the collection bucket.

The units were sustained with a continual supply of fruit and vegetables (supplied by Fresh Produce Group) or used coffee grounds and vegetable waste (supplied by local cafes). The larvae had voracious appetites. For example, an entire 'Qld Blue' pumpkin was consumed within approx. 2 days in one unit.

Apart from dark liquid waste discharged from the base of the biopod, remarkably little residue appeared to remain after processing by the larvae. The one part they were unable to consume were the plant skins, such as those on pumpkin or capsicum. The flesh would be liquidized and completely eaten, leaving behind a clean, thin, papery skin.

Figure 14 - BSF larvae consuming capsicums, viewed through the biopod hatch, with only the papery skin remaining.

8.2 Domesticating the colony

Having established BSF populations outdoors from wild stock and harvested pre-pupae, the next step was to produce a breeding colony from which eggs and/or larvae of known age and provenance could be harvested for trials.

The harvested pre-pupae were loaded into shallow trays loosely covered with mulch and placed inside an insect proof net house erected inside a glasshouse at Sydney University Darlington campus.

Figure 15 - Net house for colony establishment and tray of BSF pre-pupae.

Temperatures during the trial remained warm, rarely falling below 15^{o}C at night and generally increasing to between 25-30^{o}C during the day (Figure 16). Temperature and humidity were also recorded inside the net house. A sample week is shown in Figure 17. Temperatures inside the greenhouse generally remained 2-3^{o}C warmer than the outside air overnight. During the day temperatures inside the house ranged from 3 – 10^{o}C warmer than outside, or even more, the cooling system inside the greenhouse being inadequate to cope with hot weather.

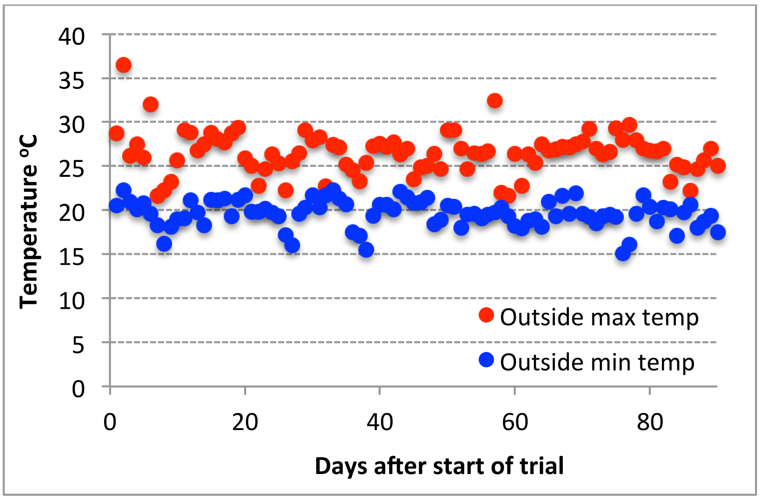

Figure 16 - Daily maximum and minimum air temperatures during colony establishment

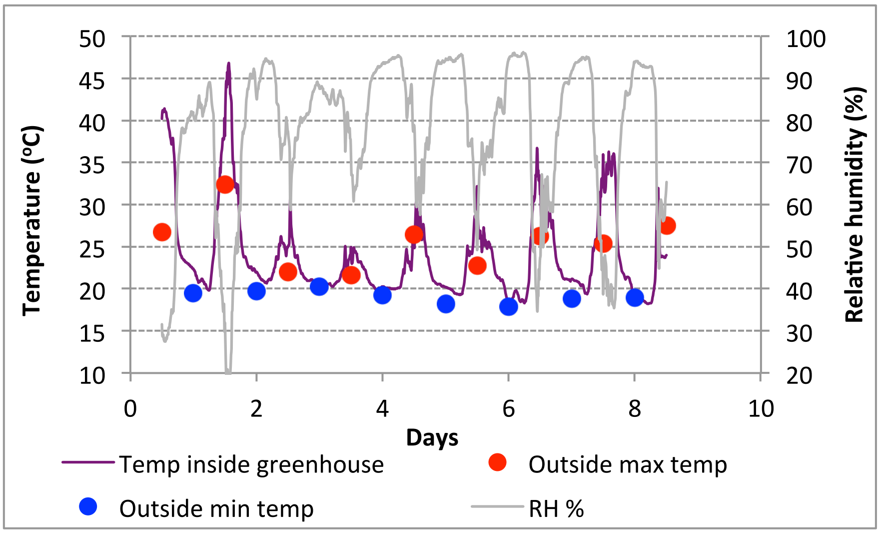

Figure 17 - Temperature and RH% inside the net house in comparison to the ambient air. Indicative data shown for one week only during mid February.

Under these conditions the initial loading of BSF pre-pupae hatched within a week. They were provided with water and a number of plants as 'lekking points'. A bucket containing well moistened layer feed was placed inside the enclosure as an oviposition lure. Multilayered cardboard blocks were taped just above the substrate, as described by Tomberlin *et al.*, to provide a suitable substrate for females to oviposit [17].

8.3 Encouraging mating

Emerging flies reportedly mate within 2-3 days of emergence and lay eggs 1-2 days after[14]. However, despite suitable temperatures and the presence of large numbers of hatched flies, no mating was observed within the first 2 weeks of flies starting to emerge and no eggs were laid on the cardboard or into the layer feed.

Previous research had indicated that that BSF require intense light to stimulate mating[11]. Although conditions during the trial were generally sunny, it seemed possible that the net house and plastic roof of the greenhouse could together be cutting down natural light such that the flies were unwilling to mate.

While other authors have reported only marginal success with artificial lighting, we considered that supplementing the natural light could encourage increased activity, especially as it would also provide a heat source. Two large metal halide lights were therefore installed, shining into the enclosure.

Figure 18 - Metal halide lamps used to supplement lighting (L) and adult black soldier flies aggregating on the plants placed near the lamps.

In addition, a Biopod was placed inside the net house, loaded with used coffee grounds. These were used partly because it had become clear that larvae could live on this feedstock, but mainly because and it is relatively easy to separate young larvae from this material by straining through a soil sieve. It was hypothesized that this would be a more strongly appealing oviposition lure than the layer mash, which tended to dry out and turn rancid after only a day or two.

Unfortunately these measures still failed to result in either mating or egg lay.

According to the literature, adult BSF do not eat, but simply require water[13]. Despite this, and having tried other measures, we decided to test whether providing a sugar source would assist. A large tub of halved apples was therefore placed inside the enclosure.

There was an immediate reaction to this, flies landing and appearing to lick juice from the cut surface of the fruit. Within days, flies had started mating (Figure 19). After two weeks young larvae were observed in both the coffee grounds and the tub of apples. None were found in the poultry layer mash.

Figure 19 - BSF adults mating on the side of a biopod

It cannot be definitely stated that providing a food source stimulated mating and oviposition. It could also be that the presence of a more suitable oviposition substrate had an effect, or that other, unknown factors influenced the result.

However, the strain of BSF found in Australia is not necessarily identical to those encountered in the US, China or other parts of the world. Fen Zhou found significant differences between BSF from different regions of China, as well as between Chinese and American strains[34]. Larval diet, environment, humidity and light may all play a role in adult behaviour. Providing sugar is essential to promoting survival in other fly species. In the case of Queensland fruit fly, adults are unable to become sexually mature without consuming both sugar and a source of protein[63]. It is therefore not surprising that providing food appeared to enhance colony fitness and activity.

Given the essential role of mating and oviposition in any future commercial production system, this area seems worthy of more detailed examination.

8.4 Testing larval quality

Previous research trials conducted with BSF have focused on pre-pupae. Harvesting at this stage has clear logistical advantages due to natural larval migration from the feedstock. During this stage larvae stop feeding, and search for somewhere dry to pupate, a process which may take several days. Researchers who have measured larval weight during development have shown that 35% or even 50% of the final larval weight can be lost during transformation into a prepupae[17].

Moreover, during transformation into a pre-pupae, the soft white skin of immature larvae becomes hardened and dry. The chitin content of larvae is a significant issue affecting the palatability of larvae to fish. We hypothesized that not only would yield be increased, but suitability for aquaculture feed would be greater, if larvae were harvested at an immature stage.

Unfortunately, developing a test for chitin was outside the scope of this project. However, samples of late instar larvae and mature pre-pupae were used to compare fat and protein content. Both were sourced from the same biopod. They were sorted by colour, killed by freezing then thoroughly dried. The dried larvae were then ground into meal for analysis.

The differences between the products were immediately noticeable. Meal made from late instar larvae clearly had higher fat content. White particles were visible and the meal had an oily texture. In contrast, the meal made from pre-pupae was more finely textured and dry.

[63] Perez-Staples D, Prabhu V, Taylor PW. 2007. Post-teneral protein feeding enhances sexual performance of Queensland fruit flies. Physiol. Entomology. 32:127-135.

Figure 20 - Ground meal made from dried, late instar larvae (top) and pre-pupae (bottom)

The samples were analyzed by George Weston Analytical Laboratory.

	Fat (g.100g^{-1})	**Protein (g.100g^{-1})**
Larvae	42.8	30.8
Pre-pupae	30.8	42.9

Larvae were higher in fat and lower in protein. As protein is the critical component used in aquaculture feed, this appears to be a negative result. However, when larval weight loss between larval and pre-pupal stage is considered, it appears that the total amount of protein.larvae^{-1} is unchanged; it is merely diluted by extra fat in the late instar larvae.

9 Black soldier fly feeding trials

9.1 Feeding trial 1 – pumpkin, carrot or sludge

9.1.1 Method

9.1.1.1 Container Preparation

Containers were prepared which had large holes cut into the lids for ventilation, a layer of filter material (polyester wadding) in the base and a drainage hole in the base of each container with tubing inserted to drain out waste. A piece of gauze was inserted in the lid to ensure insects could not escape (Figure 21).

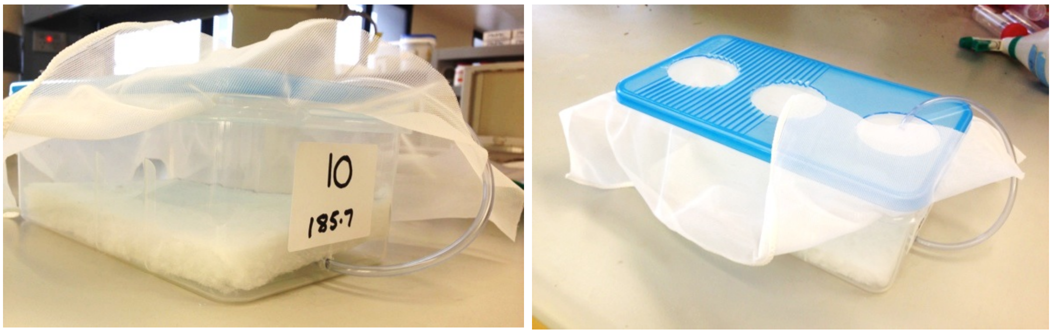

Figure 21 - Containers used for feeding trial 1, intended to resemble small 'biopods'.

9.1.1.2 Larvae

As noted in Section 5 of this report, it was not possible to retrieve eggs from the colony so as to use eggs / larvae of known age in feeding trials. Instead, immature larvae were retrieved from the colony and sorted into cohorts of similar size and apparent maturity. Two hundred similarly sized larvae were counted into twelve containers (four replicates / treatment).

9.1.1.3 Feedstock

Three feedstocks were used, with four replicates of each;

- Finely processed fresh butternut pumpkin (seeds only removed)
- Finely processed fresh carrot
- Vegetable sludge waste supplied by Moraitis Fresh processing facility. It appeared to have been previously treated with a floculant to separate water and solids. The material was therefore thoroughly strained to remove as much excess water as possible before use (Figure 22).

Figure 22 - Vegetable 'sludge' made from ground, floculated vegetable waste.

Samples of each feed type were taken for dry weight. The remaining feed was divided into small ziplock bags and frozen until required.

Two portions of feed (250-400g) were added to each container, along with 200 larvae. Containers were incubated at 27°C, with a tray of water inside the cabinet to help humidify the air. Feed was replenished every 5 days (as needed).

It was not necessary to remove any waste as the filter soaked up a relatively large volume of moisture. The large amount of ventilation provided in each container also allowed the feed to dry out.

9.1.2 Results

Water loss from the container, as well as impregnation of feed into the filter, meant it was not possible to calculate the amount of feed consumed during the trial and, therefore, the feed conversion rate. In addition, some of the larvae had become tangled in the filter material so could be easily retrieved for counting and measurement. Recording mortality under such circumstances was therefore judged to have limited value.

Weight gain was calculated by measuring a subsample of 50 larvae per treatment unit. Larvae fed on pumpkin gained significantly more weight than those fed sludge, with carrot intermediate. Gain during the 13 days of the trial ranged from 176% to 476% of initial weight (Figure 23).

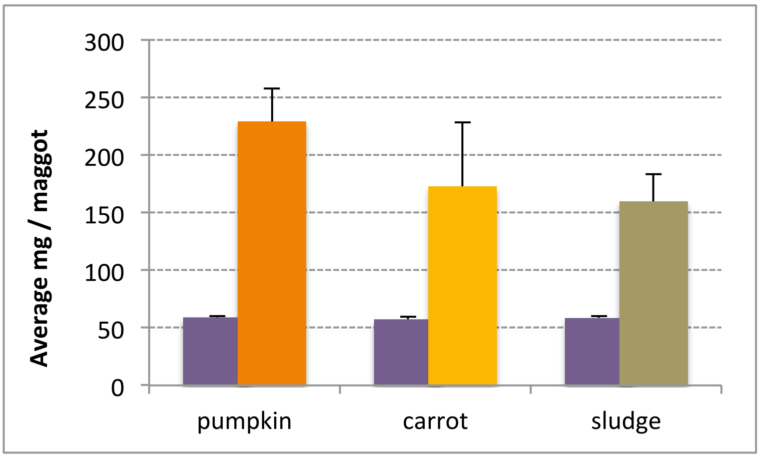

Figure 23 - Average weight per maggot at the start (purple columns) and after 13 days feeding on minced raw pumpkin, minced raw carrot or vegetable sludge. Error bars indicate the standard deviation of each mean value.

This represents approximately 13, 9 or 8mg weight gain.larvae^{-1}.day^{-1} on pumpkin, carrot and vegetable sludge respectively.

9.2 Feeding trial 2 – pumpkin, carrot or lettuce

9.2.1 Method

9.2.1.1 Container preparation

Following the experience of Trial 1, the feeding boxes design was changed. This and subsequent trials used small (350ml) clear plastic containers. A single, tiny hole (approx. 1-2mm diameter) was made in each lid. This was to allow air exchange while minimizing moisture loss.

9.2.1.2 Larvae

Twelve groups, each containing 60 immature larvae of consistent size, were isolated from the main culture as previously. Average weight.larvae^{-1} was 50.5mg.

9.2.1.3 Feedstock

Feeds used were

- Finely processed fresh butternut pumpkin (seeds only removed)
- Finely processed fresh carrot
- Shredded cos lettuce, including stem and leaves

Samples of each feed were used to measure dry weight as previously. Ziplock bags of carrot and pumpkin were frozen until needed, the shredded lettuce was simply kept refrigerated.

Each container was started with approximately 130g of pumpkin or carrot or 60-70g of lettuce (this being all that could fit in the container), as well as the 60 larvae. After 4 days liquid 'waste' was drained from each container and additional feed was added. One week after the trial was started the larvae were removed from the feed, weighed and counted to assess mortality.

9.2.1.4 Calculating feed conversion

It became clear during this trial that BSF larvae liquefy their feed in order to consume it. This is common among fly species, which often have symbiotic gut bacteria. These help to break down food so it can be absorbed. Recent work has demonstrated that fermenting a feedstock with bacteria isolated from the gut of black soldier fly larvae makes the food more easily digestible and reduces development time[64].

Due to this factor, it was not possible to separate uneaten food from waste, making it impossible to calculate an accurate feed conversion ratio. However, total weight lost from the system was calculated. This figure was corrected for moisture loss using a number of additional containers containing feed only.

It was assumed that weight loss from the system was due to respiration by the larvae. It was further assumed that respiration utilized only the dry matter portion of feed added. With

[64] GuoHui Y et al. 2010. Effect of chicken manure treated by gut bacteria on the growth and development of black soldier fly *Hermetia illucens*. Chin. Bull. Entomology. 47:1123-1127.

these assumptions it was possible to calculate the minimum amount of fresh material that would be required to produce a given quantity of dry maggot meal.

9.2.2 Results

9.2.2.1 Contamination

Two of the containers of carrot became contaminated with what appeared to be a yeast. Although the contaminated feed was removed and replaced with fresh feed, within 24 hours the growth had returned. Larvae were clearly unable to feed on the vegetable when the yeast was present. It may be that the yeast prevented symbiotic bacteria in the BSF larval gut from breaking down the feed into a digestible form.

The larvae appeared to be trying to leave the feedstock, presumably in search of an alternative (Figure 24). These containers were therefore not included in the data.

Figure 24 - Normal (L) and apparently yeast infected minced carrot in feeding containers. Far right picture shows larvae attempting to leave the feedstock.

9.2.2.2 Mortality and weight gain

Mortality was less than 5% in all three feed types. Weight gain results were similar to, while slightly higher than, those recorded from Trial 1. Larvae fed on pumpkin, carrot and lettuce gained an average of 14, 10 and 13mg per day respectively. These differences are relatively small, with the result that average maggot weight did not differ significantly among the different feedstocks at the end of the trial (Figure 25).

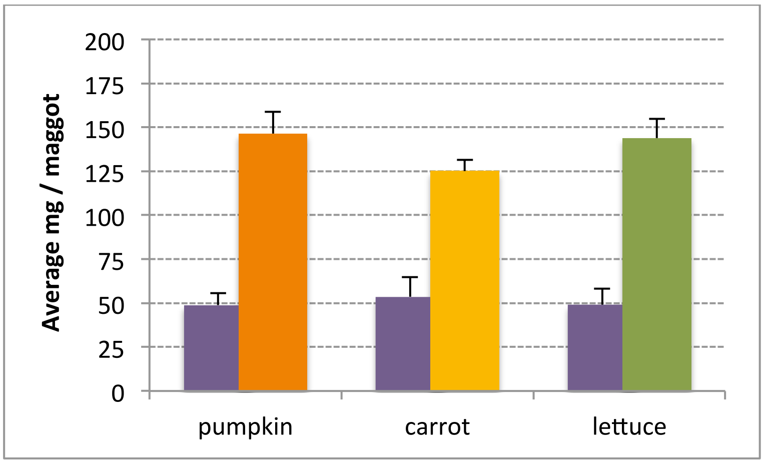

Figure 25 - Average weight per maggot at the start (purple columns) and then after 7 days feeding on minced raw pumpkin, minced raw carrot or shredded lettuce. Bars indicate the standard deviation of each mean value.

However, there were large differences in larval dry weight between the treatments. While larvae fed on pumpkin or carrot contained 32-33% dry matter, those fed on lettuce were less than 23% dry matter. When weight gain is calculated in terms of dry matter, differences between the treatments become significant. Larvae fed on pumpkin increased weight nearly 50% faster compared to those fed on lettuce (Figure 26).

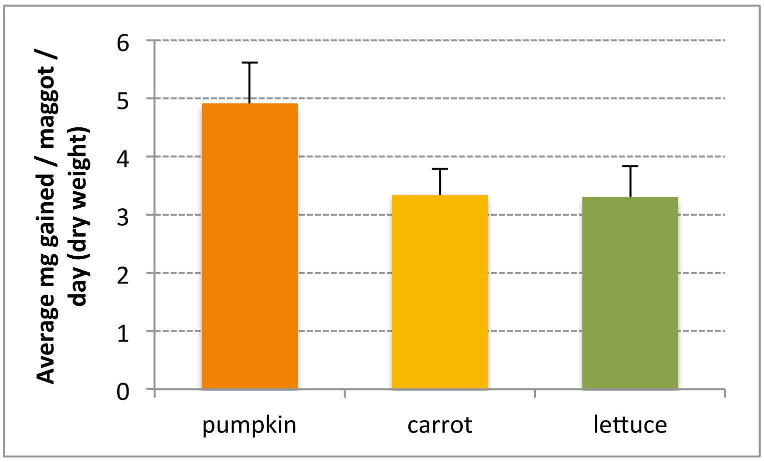

Figure 26 - Average weight gain per day during the trial. Values expressed per maggot on a dry weight basis. Bars indicate the standard deviation of each mean value.

As previously stated, feed conversion could not be measured directly due to the impossibility of separating uneaten liquefied feed from excreted liquid waste. However, it was possible to measure loss from the system – the majority of which was assumed to be due to metabolic activity by the larvae.

As this loss would consist of dry matter only, and as the percentage dry matter in the feed stocks had been measured, it was possible to estimate the *minimum* total fresh weight of feed which had been consumed.

The results suggest that a large volume of feed is required to produce a small quantity of live maggot. Based on this calculation, the average feed conversion ratios are;

- pumpkin 8:1
- carrot 10:1

- lettuce 16:1

In reality, fresh vegetables are being used to produce dried maggot meal. When this is considered the amounts of vegetable required are even greater (Figure 27). It was estimated that to produce 1kg of dried maggot meal would require approximately

- 25kg of fresh pumpkin
- 31kg of fresh carrot
- 51kg of fresh lettuce

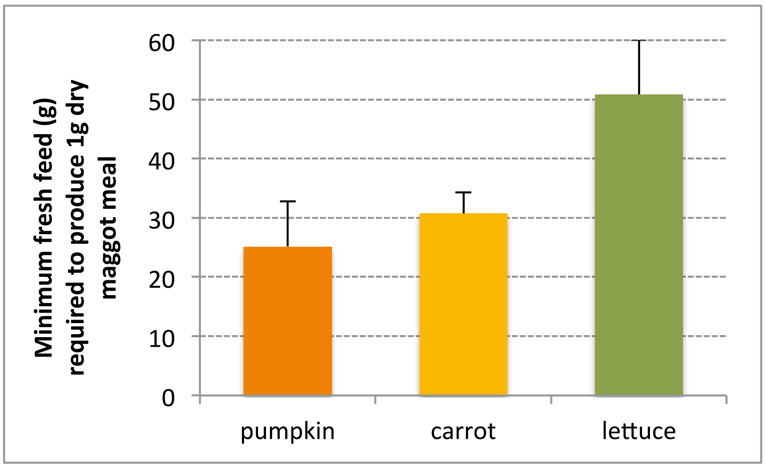

Figure 27 - Minimum quantities of fresh vegetables required to produce a given quantity of dried larval meal. Figures are based on loss from the system during growth, assuming that all mass lost was dry matter respired due to metabolic activity. No allowance is made for evaporation from each container.

This figure may be an overestimate – although efforts were taken to minimize moisture loss from the containers, some must have occurred. This evaporation will have incorrectly increased the estimate of feed required. Despite this, it seems likely that metabolic activity is a significant energy sink; larvae appear extremely active during growth, wriggling continuously while feeding.

9.3 Feeding trials 3 and 4 – a range of vegetables

9.3.1 Method

These trials were conducted concurrently, so are reported here together. Both followed a similar format to trial 2.

9.3.1.1 Larvae

Larvae were extracted from the mother colony, cleaned and sorted into cohorts of similar size. Larvae used in trial 3 were slightly averaged 45mg each, similarly to those in trial 2. Larvae in trial 4 were slightly more advanced, averaging 65mg each.

9.3.1.2 Feedstocks

Trial 3 repeated the feed sources used in the previous trials, with 4 replicate containers / treatment as previously;

- Finely processed fresh butternut pumpkin (seeds only removed)
- Finely processed fresh carrot
- Shredded cos lettuce, including stem and leaves
- Vegetable sludge waste supplied by Moraitis Fresh processing facility

Trial 4 tested 3 new feed sources;

- Chopped capsicum (de-seeded)
- Finely processed fresh kumera (sweet potato)
- Finely chopped fresh eggplant

Samples of each feed were used to measure dry weight as previously. Shredded lettuce was prepared freshly on each occasion. The other feeds were pre-prepared and kept frozen in ziplock bags until required.

Figure 28 - Feed and larvae at the commencement of trial 3. Each tub contains around 35-40g of feed, to which was added 100 young larvae.

Due to the issues with yeast growth observed in the previous trial, smaller volumes of feed were added every 3-4 days during the trial. Each container was started with approximately 35g (Trial 3) or 50g (Trial 4) of feed. After 4 days liquid 'waste' was drained from each container and additional feed was added, as previously. This was repeated twice per week until the end of the trial. The trials were continued for 17-18 days with the objective of maximizing larval yield.

9.3.2 Results

9.3.2.1 Contamination

A total of 4 containers developed 'yeast' contamination during the first 4 days of the trials and had to be discarded. Two contained pumpkin, one carrot and one kumera. No yeast growth was observed in the lettuce, waste sludge, eggplant or capsicum feedstocks. Contaminated containers were emptied, washed with chlorine and all food replaced while the larvae were also rinsed with a dilute chlorine mix. However, this did not prevent the infection returning.

9.3.2.2 Mortality

Mortality of larvae fed most of the feedstocks remained below 5% as previously. However, 17% mortality was observed in the larvae fed vegetable sludge, with more than half of the larvae fed lettuce failing to survive – average mortality reached 52%, with one container recording 68% mortality. This suggests that a diet of lettuce alone was not sufficiently nutritious to sustain the larvae for the relatively long period of time used in this trial compared to previously.

9.3.2.3 Weight gain

Although this trial ran for 10 days longer than trial 2, the end weight of the larvae was similar, ranging from 100 – 150mg.

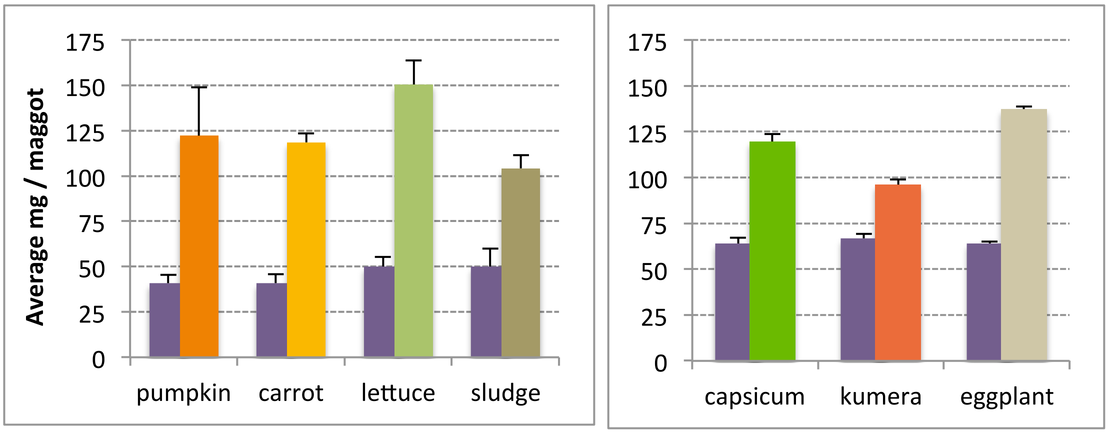

Figure 29 - Average weight per larvae at the start of each trial (purple bar) and after 17-18 days feeding on fresh vegetable. Error bars indicate the standard deviation of each mean value.

Due to the relatively long duration of the trial, the rate of weight gain by the larvae was therefore much less than previously recorded.

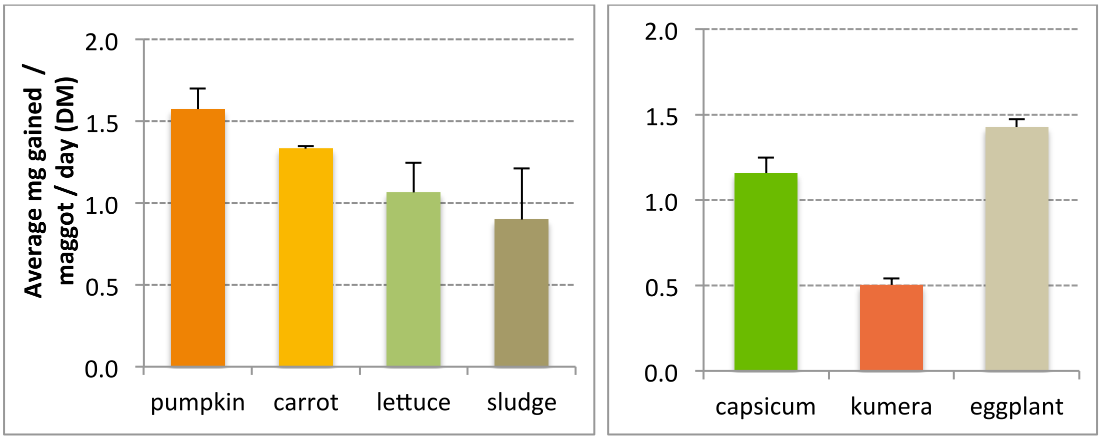

Figure 30 - Average rate of weight gain, expressed as mg dry weight.day^{-1}.larvae^{-1}, of larvae fed on various fresh vegetables. Bars indicate the standard deviation of each mean value.

In both trials, total loss of material from each container was calculated. Additional 'blank' containers were used to estimate the rate of water loss from each. Unfortunately this proved quite variable, ranging from 0.2 – 0.8ml per day. These parameters were added into the calculation as maximum and minimum losses due to evaporation. As a result, estimates of total fresh feed needed to produce 1g dried meal ranged from 126g to over 4kg.

On examining the various rates of increase, it was clear that larval growth had slowed significantly well before the trials reached completion. As shown in Figure 31, weight gain had reached its maximum within 2 weeks of trials commencing; continuing to feed the larvae after this time had less effect and it seems likely much of this feed was simply used to sustain metabolic activity.

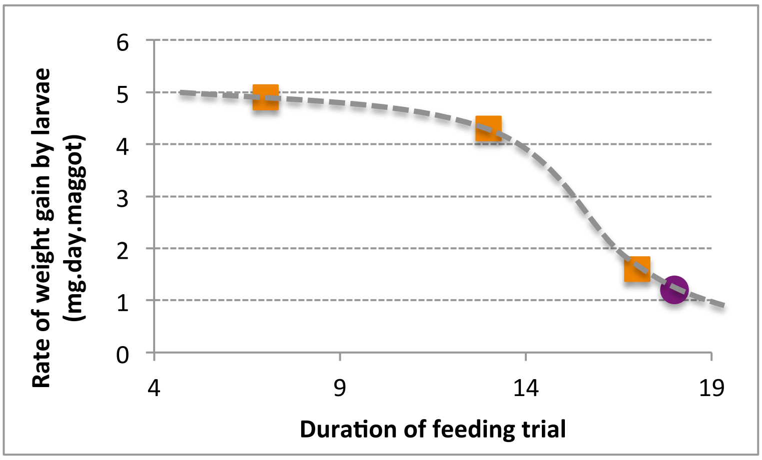

Figure 31 - Rate of weight gain of larvae in relation to duration of feeding trial. ■indicate mean rates recorded for pumpkin, ● indicates the mean rate recorded for eggplant.

These results show the importance of proper assessment of harvest maturity in maximizing productivity of larvae fed on different feed sources.

9.4 Feeding trial 5 – increasing Omega 3 content

9.4.1 Aim

The aim of this trial was to determine whether adding ground flax seed to a standard vegetable feedstock would increase omega 3 content in harvested larvae, thus increasing their suitability for aquaculture feeds.

9.4.2 Method

9.4.2.1 Larvae

Larvae were extracted from the mother colony, cleaned and sorted into cohorts of similar size. Average weight of larvae was 57.3mg. This trial used a larger number of larvae per treatment than previous trials, primarily because of the volume of dried product required for testing of fat, protein and Omega 3 fatty acids. Approximately 200 larvae were used for each treatment unit, giving a total weight of 11-12g.

9.4.2.2 Feedstocks

Flax seed was finely ground, and mixed with finely diced capsicum (seeds removed) to produce 3 feed types. Combinations were formulated to produce feeds with 0, 1% and 3% omega 3 fatty acid content. In fact, subsequent testing indicated the actual O3 contents of the feeds were slightly lower than projected. Treatment annotations are therefore noted below.

Target O3 content	Ground flax seed	Diced capsicum	Actual O3 content
0%	0	1,200g	0%
1%	46g	970g	0.8%
3%	150g	988g	2.4%

Capsicum was used because it appears to have high palatability to BSF larvae and does not suffer the issues with yeast contamination observed on feedstocks such as pumpkin and carrot (perhaps due to either its higher acid content or to rapid liquefaction by the larvae)

An initial loading of 50g feed was placed in each container along with the ~200 larvae. The containers were incubated at 27^{o}C. Every 3-4 days additional feed was added and liquid waste removed. The trial was continued for 18 days.

9.4.2.3 Processing

At the end of the trial larvae were removed, weighed, killed by freezing and dried. Dried larvae were then processed into meal using a coffee grinder, a process made more difficult by their obviously high fat content. Samples were then sent to George Weston Laboratories for analysis.

9.4.3 Results

9.4.3.1 Weight gain

Larvae fed on the 1% Omega 3 mix increased in weight nearly twice as much as the larvae fed on capsicum alone. Increases in larvae fed on the 3% Omega 3 mix were somewhat intermediate. When these weight increases were converted into dry weights the difference was even greater. Larvae dry matter increased from 27.2% to 32.2% to 34.9% with the 0, 1% and 3% Omega 3 diets respectively.

When this was included in the calculation, actual dry matter increased more than twice as much in the 1% Omega 3 diet as in capsicum alone (Figure 32).

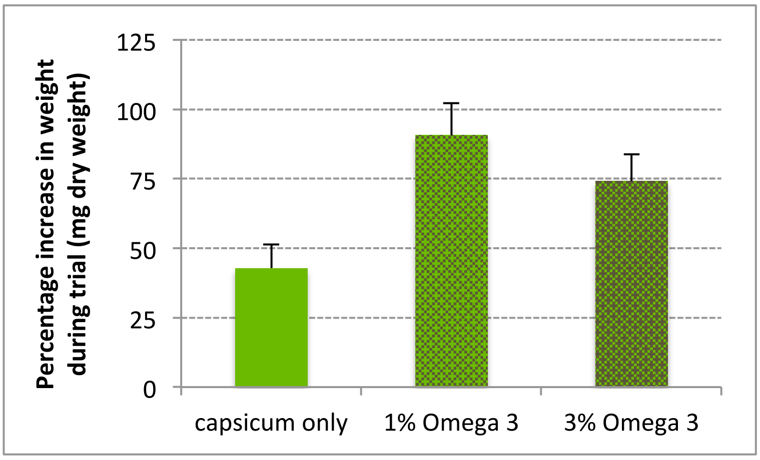

Figure 32 - Weight gain of larvae fed capsicum and ground flax seed formulated to provide 0, 1% or 3% Omega 3 fatty acids. Bars indicate the standard deviation of each mean value.

The dry weight of the feeds themselves also varied greatly due to the incorporation of the flax seed flour. Capsicum alone is around 94% water. Incorporating the flax seed increased dry matter in the 1% and 3% Omega 3 feeds to 10.4% and 17.8% respectively.

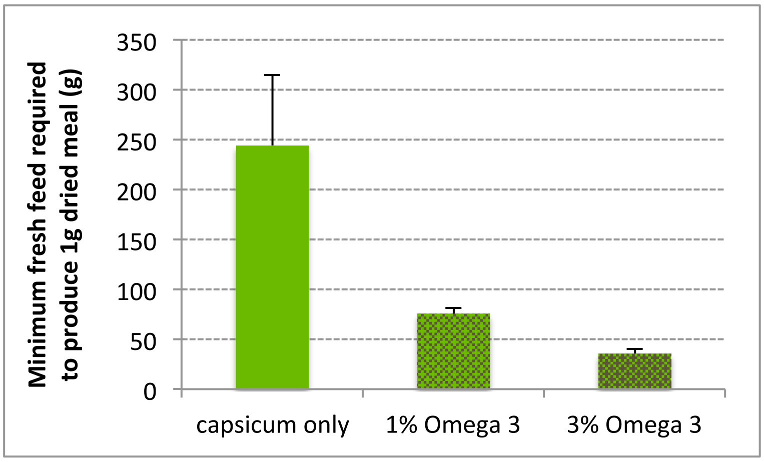

Figure 33 – Weight of fresh feed required to produce 1 g dried meal

9.4.3.2 Quality attributes

Analysis of the different larval meals showed that the method was extremely successful in increasing the Omega 3 content of the larvae. The negative impact of the method was on fat content, which also increased, with protein only slightly affected.

Feedstock	Fat ($g.100g^{-1}$)	Protein ($g.100g^{-1}$)	Omega-3 ($mg.100g^{-1}$)
Capsicum only	43.3	39.0	290
1% Omega 3	46.4	38.4	6,430
3% Omega 3	50.0	37.5	8,240

The results suggest that large increases in both yield and quality attributes of BSF larvae are possible using dietary modification. In this case it seems likely that the trial continued for longer than was optimal for larval development; it seems possible even a short period of feeding a nutritious diet high in Omega-3 fatty acids could greatly enhance the potential returns from harvested BSF larvae.

9.5 Additional, incomplete feeding trials

9.5.1 Two additional feeding trials were also conducted.

One examined whether cooking the feedstock, thereby presenting the larvae with a feed that was already partially broken down, would increase larval growth rates (an initial test using commercial pumpkin soup suggested this would be a highly suitable). This was abandoned due to the high rate of yeast infection of the feedstock.

A second trial tested cauliflower and broccoli as feedstocks. These were completely unsuitable. Although broccoli had been successfully processed by larvae when it was part of a general mixture of vegetable wastes, presented alone the larvae were unable to break it down. Both broccoli and cauliflower retained their texture; they were not liquefied as other vegetable products had been. This suggests that the BSF larvae symbiotic bacteria were unable to pre-digest these crops. In addition, containers with these products had a strong, sulfurous smell. Brassicas contain a wide range of sulfur compounds, which act as anti-feedants to some insects. It seems this makes them unsuitable for BSF production.

9.6 Discussion and Conclusions

9.6.1 Vegetable suitability

The results demonstrate that BSF larvae can be reared successfully on a range of different vegetables, with the notable exceptions of broccoli and cauliflower. Lettuce, while suitable, can only be fed to the larvae for a relatively short period. The high water content of larvae fed on lettuce indicates the large volume of feed they were taking in an attempt to meet their nutritional needs. It seems possible that although lettuce could form part of a diet, it is insufficiently nutritious alone. Kumera (sweet potato) was also non-preferred. Although energy rich, it appeared to be difficult for the larvae to break this down to consume, although it seems possible that further processing the product could help.

It became evident during these trials that BSF larvae do not feed directly on vegetables, but first reduce them to liquid. This allows them to ingest them directly. It is well recognized that many insects have non-pathological associations with bacteria. These may help break down and digest food, provide protein or act as a source of other nutrients[65]. These appear to be particularly important in polyphagous insects. That is, ones where the larvae can survive on a wide range of different feed types. No studies appear to have been done with BSF larvae, but it seems plausible that these larvae have a symbiotic relationship with one or many bacteria, which assists liquefaction and digestion of a wide range of food types.

One of the major issues encountered during these trials was the contamination of the feed with what appeared to be a yeast. Introducing larvae to the feed type appeared to start a type of 'arms race' – either the feed was liquefied and eaten by the larvae, or it remained intact and was colonized by the yeast. No samples were observed to have both yeast and larval feeding.

In feed types that were relatively easily liquefied, such as capsicum and eggplant, yeast was not an issue. Hard vegetables such as carrot and kumera which were less easily liquefied, were more likely to be colonized by the yeast. Samples of pumpkin, cooked to try to advantage the larvae, instead had the opposite effect. Unfortunately, there was not time during this project to test the effect of acidification, or use of preservatives, on the apparent microbiological battle over the food supply. However, this could be extremely important were BSF to be produced commercially. Introducing an appropriate bacteria into the media could potentially not only prevent this type of contamination occurring, but also make it easier for the larvae to feed, improving feed use efficiency and growth rate[66].

9.6.2 Yield

Dry matter content of the larvae varied significantly by feed type used. With the exception of kumera, the average dry matter content of larvae tended to follow the dry matter content of the feedstock used, as shown below. The approximate feed conversion rate for different feedstocks was estimated based primarily on Trial 2, with correction factors used to account for different trial durations.

Feedstock	%DM (larvae)	%DM (feed)	Feed Conversion ($dm^{feed}:dm^{larvae}$)
Pumpkin	32.8	14.1	3.5:1
Carrot	31.2	13.0	4.0:1
Veg sludge	28.1	11.3	11:1
Kumera	27.4	19.5	N/D
Capsicum	25.5	5.7	4.0:1
Eggplant	24.8	6.0	5.1:1
Lettuce	20.3	5.3	2.7:1

As dry matter is the harvestable product, maximizing dry matter of larvae can greatly increase the efficiency of the method. Adding 4.5% flax seed flour to chopped capsicum (by weight) increased the dry matter content of larvae by 5%, as well as more than doubling their growth. Increasing the flax seed flour content to 13% (by weight) of the feedstock increased dry matter by another 2.5% but had less effect on growth.

These results show that a relatively small addition of another feed can have a very large effect on productivity. Vegetables alone may not be a viable option for production of BSF

[65] Drew RAI, Lloyd AC. 1989. Bacteria associated with fruit flies and their host plants. In "Fruit flies. Their biology, natural enemies and control. Eds AS Robinson, G Hooper. Elsevier Press. Pp131-140.
[66] Hansen AK, Moran NA. 2014. The impact of microbial symbionts on host plant utilization by herbivorous insects. Mol. Ecol. 23:1473-1496.

larvae for fishmeal. This is due to the large quantities of fresh vegetables required compared to the amount of dried meal produced.

It was estimated in trial 2 that 6-11g of pumpkin or carrot would be required to produce 1g BSF larvae, with an average of 8.6g needed. However, the end product of this process is dried meal. Converting these figures to dried weight suggests that an average of 27g fresh carrot or pumpkin would be needed to produce a single gram of dried meal.

However, the results from the final trial suggest that adding even a small component of another product – in this case flax seed flour - can reduce the raw materials required by 70-85%.

9.6.3 Quality attributes

Larvae grown on a diet including an additive such as flax seed flour may not only grow faster, but have greater value for use in aquaculture. The economic viability of the method then starts to look more likely. In this case, Omega-3 fatty acids were increased from a negligible 290mg.100g^{-1} to 6,430mg.100g^{-1} or more by including 4.5% flax seed in the diet.

One of the reasons fishmeal is an essential part of aquaculture feeds is its content of omega-3 fatty acids – linolenic, docosahexaenoic (DHA) and eicosapentaenoic (EPA). All of these compounds are essential for normal development and growth of the fish. Whereas most plants contain linoleic acid (an omega-6 fatty acid), flax seeds are predominantly linolenic acid. However this cannot be easily converted into DHA and EPA within the fish.

The samples produced in this trial were not large enough to allow full analysis of the larval omega-3 content into its component parts, including DHA and EPA. However, the results appear promising in this regard, and worthy of more investigation.

Protein content in the dried meal was similar to that in many aquaculture feeds. Although high quality fishmeal contains 60-72% crude protein, typical diets for fish may be around 32-45% protein while those for prawns are even lower at 25-42% protein. The dried BSF larvae contained 31-37% protein, while the prepupae were 43% protein.

The amino acid profile and digestability of protein is a critical factor affecting its suitability for aquaculture feeds. For example, the protein in fishmeal is 95% digestable and contains all the amino acids fish need. Proteins from plants, such as soy, may be only 75% digestable and lack a number of essential amino acids. Analysing the protein profile of BSF fed on different feedstocks would be needed to accurately determine suitability for fish.

The dried BSF also contained 40-50% fat, which is much higher than that in fishmeal. Fishmeal contains a mixture of solid fats and oils, which can range from 4-20% but is generally around 6-10%. Chitin content was not measured in this trial, but would also be undesirable in the end product due to its antifeedant properties. The results of these trials therefore reinforce the recommendation in Section 5.9 of this report that dried BSF would need to be rendered into their component parts before formulation into a feed.

9.6.4 Future research

CSIRO recently announced the development of Novacq™, an additive to prawn feed. The sustainably produced product has been shown to improve prawn health and increase growth rate by 30% without compromising taste or quality. The product has taken 10 years, a huge research team and many $millions, but is now licensed to Ridley AgriProducts in a deal potentially worth $billions.

The development of BSF as an aquaculture feed has barely begun. Major investment is needed if this is to be commercially developed. While a diet rich in vegetable wastes could clearly be part of this process, it seems unlikely that vegetables alone can provide fast and efficient enough growth to make this method economically viable. Consideration also has to be given to the fat, protein and other component profile of the dried meal in terms of its suitability for aquaculture species – this is an area which will require extensive (and expensive) research if it is to progress beyond this initial stage.

10 Economic viability of soldier fly production

10.1 Introduction

Many factors affect the economics of using Black Soldier Fly (BSF) to convert vegetable waste to a protein meal suitable for use in industrially manufactured compound aquafeeds and / or as feed for poultry and pigs. The supply of vegetable waste, alternative uses of waste, costs of producing BSF meal and the price of alternative protein sources including fishmeal all affect viability. The benefits or revenues from BSF larvae sales, avoided costs of existing waste management practices, and the costs of larval production and processing all need to be estimated – a difficult process given the limited information available.

Economic benefits or revenues derive from reducing the costs of waste management as well as the sale of harvested BSF larvae. Depending on the scale and sophistication of the operation, other benefits may be generated from the sale of by-products including oil/biodiesel, chitin and fertilizer. The quantity of larvae produced in a year can be estimated from the quantity of vegetable waste produced on a farm in a year (tonnes per ha per year) and the estimated dry matter feed conversion rate for the particular vegetable feedstock (kg feed: kg larvae). Given that the harvested larvae can substitute for fishmeal or soy meal in compound aquafeeds and in feed rations for pigs and poultry, current market prices for fishmeal and soy meal can be used to estimate the value of larvae harvested annually from vegetable waste for a given vegetable feedstock.

In a farm situation the costs of waste management may be offset or exceeded by the benefits of using vegetable waste as a green manure crop or as livestock feed. Unharvested vegetable crops may be ploughed in or grazed by livestock. Post-harvest farm wastes can be fed to livestock, composted, buried or transferred to land fill. The net costs or benefits of existing waste management practices can be included with the estimated value of larvae sales to determine an estimate of the total economic benefit of using BSF to manage on-farm vegetable wastes.

Costs of BSF larvae production comprise fixed costs and variable costs. Fixed costs are determined by the scale of wastes and the end product(s). The costs of establishing a waste conversion facility to produce larvae is common to all production options. The fixed costs of the refining process include equipment to render or expel lipids from larval material, a dryer and a feed pellet production machine to produce floating and sinking aquafeed pellets and equipment to extract chitin. Where the by-products are processed then there are additional fixed costs for biodiesel production and processing of fertilizer products.

Among the factors that are likely to have the a significant impact on the economics of BSF larvae production from vegetable waste are the dry matter feed conversion rate, the scale of the operation - which is related to the quantity of waste to be managed within a given time period such as a day or week - and the price of fishmeal and fish oil and other protein feeds used in aquafeed.

10.2 Estimating the benefits

The first component is to estimate the production of BSF larvae and their value. The second component is to estimate the net costs or benefits of current management practices for handing pre-harvest and post-harvest wastes on-farm. The methods used to estimate economic benefits is based on previous research by Amatya (2009) on the use of BSF to reduce cow manure accumulation in intensive dairy operations in Erath County, Texas[67].

10.2.1 Vegetable waste supply

The feedstock for BSF larvae production is the vegetable waste remaining after harvest and post-harvest packing on farm. There are a number of waste supply factors affecting BSF conversion effectiveness:

- The quantity of vegetable waste (kg/week) on an individual farm or within a local area
- Continuity or regularity of supply of vegetable waste (number of weeks per year when waste is available)
- The type of vegetable waste
- The quality of the vegetable waste
- Weather conditions, especially temperature and relative humidity, during harvest or when wastes are generated.

10.2.1.1 Quantity of vegetable waste

The quantity of vegetable waste available is a key factor determining the scale of a BSF larvae production system. Quantity of waste produced on an individual farm is a function of the area of production, the yield per hectare and unit price paid to the producer. If the farm gate price is low or the crop has been damaged by pests or disease, then it may not be viable to harvest the whole crop. Farm waste is also generated post-harvest with produce that fails to meet minimum quality standards such as size, shape and colour, culled. Table 2 presents data on pre- and post-harvest wastes for selected vegetables.

Table 2 - Pre- and post-harvest waste for carrot, capsicum and lettuce crops

Vegetable	Yield (tonne/ha)	Pre-harvest losses (%)	Post-harvest losses (%)
Carrots	65	0	33
Capsicum	52	14	8
Lettuce (Head)	27	10	5

Source: Rogers, G, Ekman, J and Titley, M 2013. *Identifying new products, uses and markets for Australian vegetables: A desktop study*. Horticulture Australia. Project No. VG12046. April 2013

10.2.1.2 Pattern of vegetable waste supply

The supply of vegetable waste is seasonal, coinciding with the period over which the crop is harvested. Table 3 shows the harvest periods for a selection of vegetable crops grown in the Lockyer Valley in Queensland.

[67] Amatya, Prashant 2009. Economics of Black Soldier Fly in Dairy Waste management, M Sc Thesis, Tarleton State University, Texas, USA, August.

Table 3 - Harvest periods for carrot, capsicum and lettuce crops, Lockyer Valley Queensland

Crop	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Carrots							■	■	■	■	■	
Capsicum	■	■	■	■								■
Lettuce				■	■	■	■	■	■	■		

Source: Queensland Dept of Agriculture, Fisheries and Forestry. *Vegetable production in South East Queensland.* http://www.daff.qld.gov.au/plants/fruit-and-vegetables/vegetables/vegetable-production-in-south-east-queensland

10.2.1.3 Type of vegetable waste

The type of waste is determined by the specific vegetables harvested. While vegetable producers in Australia grow more than one type of vegetable, production of different vegetables often occurs in different seasons. For example, in 2011–12, 45% of vegetable growing farms in Australia grew at least two types of vegetables, with 8% of producers growing five or more different vegetable types[68]. Therefore, the vegetable waste stream on most farms is likely to be homogeneous with regard to vegetable type.

10.2.1.4 Quality of vegetable waste

Quality of waste is dictated by the requirements of the BSF larvae for growth and survival and the characteristics of the vegetable material provided as feedstock. Organic material with high lignin content cannot be digested effectively by the larvae. However, as indicated in section 5.6.2, lignin is extremely low in most vegetable crops. Cauliflower and broccoli were found to be unsuitable feeds when supplied exclusively, although they were consumed when fed as part of mixture of vegetable wastes. The presence of sulphur compounds in brassicas is likely to act as an antifeedant for BSF larvae. It was found that lettuce on its own is insufficient to meet the nutritional needs of the larvae and is better fed as a component of a diet. During feeding trials hard vegetables, such as pumpkin and carrots were subject to contamination by yeast which caused the larvae to stop feeding and to seek alternative feed sources. The nutritional quality of waste may be improved through the addition of other products, such as the flax seed used in trial 5 (Section 9.4).

10.2.1.5 Temperature and humidity conditions

Temperature and humidity are critical to the growth and development of BSF larvae. Larvae stop feeding at temperatures below 15°C. Larval feeding and development increase with temperature up to a maximum of 35°C to 36°C. Larvae can be raised in a controlled environment such as a greenhouse to ensure that temperatures remain in the optimal range for larval development and survival. Humidity is important for egg hatch and adult emergence.

Vegetable growing areas in Australia with suitable temperature and humidity throughout the year are confined to locations in Queensland. In the other states suitable temperature and humidity conditions for BSF larvae production are available for shorter periods, which will affect the economic viability of investment in BSF conversion equipment and facilities.

[68] Valle, H, Caboche, T & Lubulwa, M 2014, *Australian vegetable growing farms: An economic survey, 2011–12 and 2012–13*, ABARES Research report 14.1 prepared for Horticulture Australia Limited, Canberra, February, p.7.

Table 4 presents monthly mean minimum temperatures for the vegetable growing regions of the Lockyer Valley (Gatton) and Bowen in North Queensland.

Table 4 - Monthly mean minimum temperatures, Gatton and Bowen Queensland

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Gatton	19.3	19.3	17.4	14.1	10.9	7.6	6.2	6.8	9.6	13.1	15.8	18.2
Bowen	24	23.7	22.9	20.9	17.9	15.4	14.2	15.1	17.3	20.2	22.3	23.5

Source: Bureau of Meteorology. *Climate statistics for Australian sites. Queensland*.
http://www.bom.gov.au/climate/averages/tables/ca_qld_names.shtml

The temperature data shown in Table 3 reveals that in the Lockyer Valley there are seven months when the mean minimum temperature falls below 15°C, while in Bowen there is only one month when the mean minimum is below 15°C.

Comparing the mean minimum temperature data in Table 4 with the harvest period data in Table 3 provides an indication of the potential feasibility of BSF larvae production at each location. Table 5 presents the coincidence of harvest period and suitable monthly minimum temperature for Bowen and Gatton for carrots, capsicum and lettuce.

The data indicates that wastes from capsicum production in the Lockyer Valley can be processed by the BSF larvae between December and April, while waste from carrots can be effectively reduced using BSF larvae in November only. In Bowen, capsicum wastes can be used as feedstock for BSF larvae production between May and November, with the exception of July. Pumpkin could be used between August and November.

Table 5 - Months in which temperature conditions and vegetable waste supply coincide for BSF larvae production

Location	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
Lockyer Valley												
Capsicum	■	■	■	■								■
Lettuce												
Carrots											■	
Bowen												
Capsicum					■	■		■	■	■	■	
Pumpkin								■	■	■	■	

Mean minimum temperatures are long-term average daily minimum air temperatures. Low mean minimum temperatures appear likely to reduce the viability of a BSF conversion facility in the Lockyer Valley. However, if a waste conversion facility is located within a building or with some protection from temperature fluctuations, then minimum temperatures inside the facility and inside the conversion unit would be higher than the recorded means, which are outside temperatures. Furthermore, data are presented for a small selection of vegetables compared to the range of vegetables that are grown throughout the year in both locations. In view of this supplies of suitable vegetable waste would be available in most months of the year at both locations.

Greenhouses can be used to maintain cultures at temperatures adequate for growth and development. The number of Queensland producers using greenhouses for vegetable production is low compared to numbers in the southern states[69]. Access to and cost of greenhouse space would be a factor in determining the net benefits of BSF larvae production from vegetable wastes in Australia's southern states.

10.2.2 Value of BSF larvae production

Estimates of the value of BSF larvae vary according to the type of vegetable used as feedstock, the dry matter (dm) content of the vegetable feedstock and the dm conversion rate of the larvae. Estimates are presented for three of the vegetables that were included in the BSF feeding trials and for which data on farm waste production are available[70]. They are carrots, capsicum and lettuce. May 2014 prices for fishmeal and soy meal in Australian dollars were obtained from the Index Mundi website[71] .Table 6 presents the estimated values of the BSF larvae for the three vegetable types.

The estimated BSF larvae values in Table 5 are based on vegetable waste production during the harvest months for each of the three crops, as grown in Queensland. It is assumed that BSF larvae are productive during the harvest months when feedstock is available. The estimated BSF larvae values are expressed on a per hectare basis.

The results reveal differences in values between the vegetable types reflecting differences in the characteristics of the feedstock, especially dm content, the quantity of waste produced and differences in dm conversion rate. Variations in these parameters affect the quantity of BSF larvae produced per ha per year. The larvae values also depend on the prices of fish meal and soy meal. Variations in these prices affect the value of the larvae or the revenue generated per ha per year from the sale of BSF larvae.

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[69] According to Protected Cropping Australia in 2008 there were 80 producers growing vegetables under 30 ha of greenhouse compared to 680 growers and 500 ha in NSW, 200 growers and 200 ha in Victoria and 650 growers and 500 ha in South Australia. - http://www.protectedcroppingaustralia.com/About

[70] Rogers, G, Ekman, J and Titley, M 2013. *Identifying new products, uses and markets for Australian vegetables: A desktop study*. Horticulture Australia. Project No. VG12046. April

[71] http://www.indexmundi.com/

Table 6 - Estimated values of harvested BSF larvae fed on carrots, lettuce and capsicum

Parameter	Units	Carrots	Lettuce	Capsicum
Vegetable yield	tonnes/ha	65	27	52
Harvest months	months/year	6	6	5
Pre-harvest waste	%	0	10%	18%
Post harvest waste	%	33%	5%	8%
Total waste	tonnes/ha/yr	21.45	4.05	13.52
Waste per harvest month	tonnes/ha/month	3.575	0.675	2.70
Dry matter content of vegetable	%	13.0%	5.3%	5.7%
Pre-harvest waste (DM basis)	tonnes/ha	0	0.1431	0.53352
Post-harvest waste (DM basis)	tonnes/ha	2.7885	0.07155	0.23712
BSF dry matter conversion rate	%	25%	37%	25%
Larval yield	kg/ha/year	697.13	79.5	192.66
Larval yield per harvest month	kg/ha/month	116.19	13.25	38.532
Fish meal price (Peru 65% Protein CIF)	$/tonne	$1,954	$1,954	$1,954
Soy meal price (48% Protein)	$/tonne	$583	$583	$583
Value of larvae (fish meal substitute)	$/ha/yr	$1,362	$155.34	$376.46
Value of larvae (soy meal substitute)	$/ha/yr	$406	$46.35	$112.32

Note: Fishmeal and soy meal prices are at May 2014 in Australian dollars, obtained from http://www.indexmundi.com/commodities/

The estimates in Table 5 assume that BSF meal can substitute directly for fishmeal or soy meal in aquafeeds. However, the protein content of pre-pupae raised in the feeding trials was 42.9% whereas the protein content in fishmeal is 65% and soy meal has a protein content of 48%. The estimation of BSF larvae values were adjusted to account for the difference in protein content between BSF larvae, fishmeal and soy meal. The revised BSF larvae values are presented in Table 7.

Table 7 - Revised BSF larvae values after adjusting for differences in protein content

Parameter	Units	Carrots	Lettuce	Capsicum
Value of larvae (fishmeal substitute)	$/ha/yr	$901.14	$102.77	$249.04
Value of larvae (soy meal substitute)	$/ha/yr	$364.09	$41.52	$100.62

These values are equivalent to $1.29 per kg of BSF larvae and $0.52 per kg of larvae for fishmeal substitution and soy meal substitution, respectively. Costs of larvae production need to be less than these values for investment to be viable.

10.2.2.1 The benefits of Omega 3 supplementation to the vegetable feedstock

As described in section 9.4 feeding trials were conducted to assess the effect on larvae growth of addition of ground flax seed to capsicum to produce feeds with 0, 1% and 3% Omega 3 fatty acid content. For the 1% diet flax seed was included at 4.5% by weight, while for the 3% Omega 3 diet flax seed represented 13% of the total weight of the feed. The price of flaxseed was set at $750 per tonne. The impacts of adding flax seed to the diet on the production and economic value of BSF larvae are presented in Table 8.

Table 8 - Estimated values of BSF larvae fed diets of capsicum with 0%, 1% and mix and 3% Omega 3

Parameter	Units	0% Omega 3	1% Omega 3	3% Omega 3
Vegetable yield	tonnes/ha		52	
Harvest months	months/year		5	
Pre-harvest waste	%		18%	
Post harvest waste	%		8%	
Total waste	tonnes/ha/yr		13.52	
Waste per harvest month	tonnes/ha/month		2.70	
Dry matter content of vegetable	%	5.7%	10.4%	17.8%
Pre-harvest waste (DM basis)	tonnes/ha	0.53352	0.97344	1.66608
Post-harvest waste (DM basis)	tonnes/ha	0.23712	0.43264	0.74048
Ground flax seed in diet	%	0%	4.53%	13.20%
Ground flax seed	kg/ha/year	0	612	1782
BSF dry matter conversion rate	%	25%	32.2%	34.90%
Larval yield	kg/ha/year	192.66	452.76	839.89
Larval yield per month	kg/ha/month	38.532	90.55	167.98
Fish meal price (Peru 65% Protein CIF)	$/tonne		$1,954	
Soy meal price (48% Protein)	$/tonne		$583	
Flaxseed price	$/tonne		$750	
Value of larvae (fish meal substitute)	$/ha/yr	$376.46	$884.69	$1,641.14
Value of larvae (soy meal substitute)	$/ha/yr	$112.32	$263.96	$489.66
Cost of flaxseed	$/ha/year	0	$459.09	$1,336.56
Net value of larvae (fish meal substitute)	$/ha/year	$376.46	$425.59	$304.59
Net value of larvae (soy meal substitute)	$/ha/year	$112.32	-$195.14	-$846.90

The benefits of adding flax seed to the feed mix include increased larval yield and enhanced Omega 3 content of the larvae, improving the attractiveness of BSF meal as a fishmeal substitute in manufactured compound aquafeeds. However, accounting for the cost of the added flax seed reduces the value of the BSF larvae for some options. The feasibility of the Omega 3 diet is sensitive to the price of flax seed.

The results shown in Table 8 reveal that BSF meal with 1% and 3% Omega 3 is uncompetitive with soy meal. On the other hand, the value of the BSF larvae is 22% higher for the 1% Omega 3 diet mix than for the diet without the addition of flax seed. For the 3% Omega 3 diet mix, the BSF larvae returns are positive but lower than the return for the diet without flax seed supplementation. The additional cost of the flax seed supplementation exceeds the additional benefits associated with a higher DM conversion rate and the higher dm content of the diet.

The estimated BSF larvae values adjusted for differences in protein content in fishmeal, soy meal and BSF larvae are presented in Table 9.

Table 9 - Revised BSF larvae values after adjusting for differences in protein content

Parameter	Units	0% Omega 3	1% Omega 3	3% Omega 3
Value of larvae (fish meal substitute)	$/ha/yr	$249.04	$585.26	$1,085.68
Value of larvae (soy meal substitute)	$/ha/yr	$100.62	$236.46	$438.65
Cost of flaxseed	$/ha/yr	$0.00	$459.09	$1,336.56
Net value of larvae (fish meal substitute)	$/ha/yr	$249.04	$126.16	-$250.88
Net value of larvae (soy meal substitute)	$/ha/yr	$100.62	-$222.63	-$897.91

10.2.3 Costs of current waste management practices

Reducing the costs of managing on-farm vegetable wastes is the other potential source of revenue associated with the use of BSF. However, the size of the cost saving depends on the particular practice used by vegetable producers to reduce wastes. Options include:

1. Plough in as a green manure crop (farm wastes)
2. Feed to livestock
3. Dispose to land fill (processing wastes)
4. Other uses as identified in Figure 1

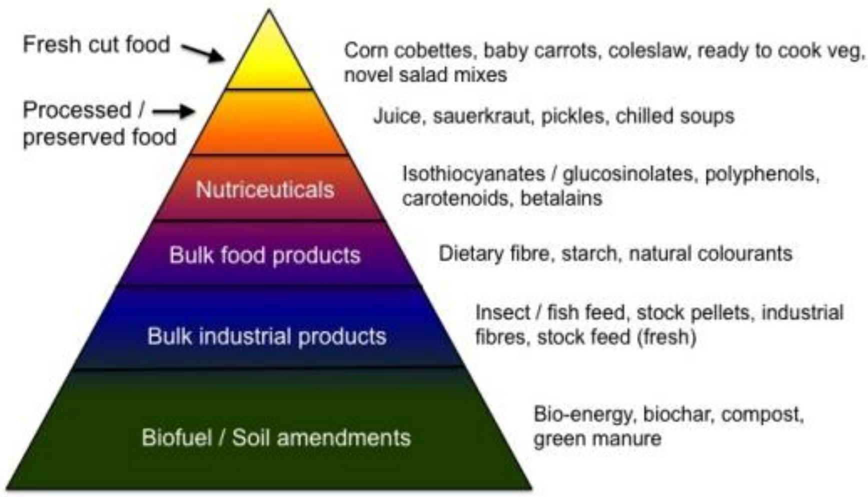

Figure 34 -Hierarchy of alternative uses for waste. Products at the top are the highest value, but utilize smaller quantities and higher qualities of raw materials compared to those at the base.

Source: Rogers et al., 2013, p.72

10.2.3.1 Green manure

The cost of ploughing in an unharvested crop was estimated at $65/ha for capsicum and lettuces[72]. This cost is avoided if the crop is harvested. However, harvesting costs for capsicum are high, being a labour intensive activity. Labour is used for picking, grading and packing. Other costs include cartons, cooling, tractor running costs, quality assurance and pallet hire. The cost of harvesting capsicum in Queensland is $16,209 per ha.

However, the cost of recovering vegetables that were not suitable or economic to harvest would be lower as many post-harvest costs are avoided. For example, the cost of harvesting a capsicum crop as feedstock for a BSF conversion is estimated to be about $4,000 including allowance for the avoided cost of ploughing in the crop. This greatly exceeds the estimated returns from BSF larvae sales as presented in Tables 6 and 7, making the option non-viable for capsicum. The harvesting costs are similar for lettuces as well. Post-harvest waste can be readily transferred to feedstock for BSF conversion with the handling costs likely to be very similar for alternative uses of the waste such as burying, composting or feeding to livestock.

[72] From Queensland DAFF vegetable gross margins

Table 10 - Estimated values of harvested BSF larvae fed post-harvest waste only (protein adjusted prices)

Parameter	Units	Carrots	Lettuce	Capsicum	Capsicum 1% Omega 3	Capsicum 3% Omega 3
Vegetable yield	tonnes/ha	65	27	52	52	52
Harvest months	months/year	6	6	5	5	5
Pre-harvest waste	%	0%	0%	0%	0%	0%
Post harvest waste	%	33%	5%	8%	8%	8%
Total waste	tonnes/ha/yr	21.45	1.35	4.16	4.16	4.16
Waste per harvest month	tonnes/ha/mth	3.575	0.225	0.83	0.83	0.83
Dry matter content of diet	%	13.0%	5.3%	5.7%	10.4%	17.8%
Pre-harvest waste (DM basis)	tonnes/ha	0	0	0	0	0
Post-harvest waste (DM basis)	tonnes/ha	2.7885	0.072	0.237	0.433	0.740
Flax seed in diet mix	%	0	0	0	4.53%	13.20%
Ground flax seed	kg/ha/year	0	0	0	188.3	548.3
BSF dry matter conversion rate	%	25%	37%	25%	32.2%	34.9%
Larval yield	kg/ha/year	697.13	26.5	59.28	139.31	258.43
Larval yield per harvest month	kg/ha/mth	116.19	4.42	11.856	27.86	51.69
Fish meal price (Peru 65% Protein CIF)	$/tonne	$1,954	$1,954	$1,954	$1,954	$1,954
Soy meal price (48% Protein)	$/tonne	$583	$583	$583	$583	$583
Flax seed price	$/tonne	$750	$750	$750	$750	$750
Value of larvae (fish meal substitute)	$/ha/yr	$901.14	$34.26	$76.63	$180.08	$334.06
Value of larvae (soy meal substitute)	$/ha/yr	$364.09	$13.84	$30.96	$72.76	$134.97
Cost of flaxseed	$/ha/yr	$0	$0	$0	$141.26	$411.25
Net value of larvae (fish meal substitute)	$/ha/yr	$901.14	$34.26	$76.63	$38.82	-$77.19
Net value of larvae (soy meal substitute)	$/ha/yr	$364.09	$13.84	$30.96	-$68.50	-$276.28

If the costs of recovering an unharvested vegetable crop or diverting unsuitable and uneconomic produce after harvest (produce that would otherwise not be harvested) exceed the returns from feeding the produce to a BSF larvae conversion facility, then it is uneconomic to use pre-harvest wastes. The returns from BSF larvae production using only post-harvest vegetable waste are presented in Table 9. The results reveal significant reductions in the values of larvae for lettuce and capsicum due to the inclusion of post-harvest wastes only. Under these conditions the production of BSF larvae meal will have to be very efficient to keep cost below the estimated returns.

10.2.3.2 Feeding wastes to livestock

This is a viable option for vegetable producers that have livestock. There are few additional costs associated with this option as unharvested crops can be grazed in the field where they were left. There are additional costs involved in feeding post-harvest wastes to livestock including collection, storage and distribution. Feeding wastes to livestock generates a benefit in the form of avoided feed costs and through higher growth rates and faster livestock turn-off rates. The feeding response is likely to vary according to the particular vegetable being grazed. If the unharvested crop is recovered for BSF conversion, then the added costs of picking and grading and feeding the waste into BSF conversion units have to included in the estimation of net benefits. These costs are similar to those for the green manure production scenario which were found to exceed the estimated revenues fro BSF larvae sales. Post-harvest wastes involve similar costs of handling whether the waste is fed to livestock or fed to BSF larvae.

10.2.3.3 Disposing farm wastes to landfill

This is an unlikely option for vegetable growers unless they operate on a very small site and cannot utilise vegetable wastes on-farm. Where post-harvest wastes are transferred to landfill, there is potential to avoid all or part of the cost by diverting the waste to an on-farm BSF conversion facility. For example, the cost of diverting post-harvest waste from a capsicum crop in Queensland from landfill is $124/tonne. Post harvest wastes for capsicum are 8% of production or 4.16 tonnes/ha. If all the waste is diverted to an on-farm BSF conversion facility, then a saving of $515.84 per ha can be made. This avoided cost can be added to the estimated revenue from selling BSF larvae (from. For example in the case of capsicum waste:

Value of larvae (fishmeal substitute) from Table 9	$76.63
Avoided landfill costs	$515.84
Total economic benefit	$592.47

For vegetable growers in this situation, the added benefits improve the attractiveness of BSF larvae. The value of harvested larvae in this production scenario is $9.99 per kg, compared to $1.29 per kg where wastes are retained on-farm. However, this option remans unlikely even for small intensive producers because if they are unable to use wastes for other purposes the same limitations may affect retention of wastes as feedstock for BSF.

10.2.3.4 Other uses of vegetable wastes

The opportunity to channel wastes to one or more of the higher-value waste streams shown in Figure 34 is likely to be low as these uses will only absorb a small share of the total waste stream. These options are not considered.

10.3 Estimating the costs

The costs of integrating BSF larvae production into vegetable waste management on an individual farm include fixed and variable costs. Fixed costs are associated with building space and facilities, a greenhouse to sustain an adult breeding colony of black soldier fly, waste conversion units for raising the BSF larvae and for the breeding colony and various items of equipment. Existing equipment used for handling post-harvest waste is likely to be suitable for transferring waste to a BSF conversion facility. A dedicated greenhouse or space in an existing greenhouse may be an option in some locations to ensure that optimal temperature conditions are sustained. Depending on the end product of the process the facility may also require processing equipment including a freeze dryer, rendering equipment, a grinder, pelletising or extrusion equipment and packaging equipment.

Variable costs include labour, water and electricity and a range of consumables. If the vegetable feedstock is supplemented with purchased inputs such as flax seed to increase Omega 3 content in harvested larvae, then these costs must be included.

Based on the findings of Veldkamp et al (2012) the costs of producing BSF larvae can be minimized by adopting one or more of the following strategies[73]:

- Maximising the feeding efficiency of the larvae – feed conversion rate
- Minimizing labour requirements - minimising labour costs
- Using automation, mechanisation and sensor technology
- Achieving economies of size which may require sourcing vegetable waste from other farms, processors and other waste producers; scaling up will reduce the average costs of buildings and facilities to house the operations
- Minimising energy consumption and costs of electricity and fuel
- Separating BSF larvae production and refinement to end products (achieve economies in refinement with distributed production of larvae)
- Maintaining environmental conditions for optimal feed conversion efficiency
- Maximizing end product harvesting efficiency.

10.3.1 Factors affecting costs

The scale of investment in facilities and equipment is influenced by the quantity of vegetable waste. The estimated daily rate of post-harvest waste production for carrots, lettuce and capsicum is as follows:

- Carrots 119 kg/ha/day over a 6 month harvest period
- Lettuce 7.5 kg/ha/day over a 6 month harvest period
- Capsicum 90 kg/ha/day over a 5 month harvest period

The decision to invest in a BSF facility depends on the expected quantity of waste generated and the pattern of the waste stream throughout a year. For an individual farm, the quantity of waste depends on the area harvested and the yield. However, the amount of waste generated is not predictable, nor is it likely to be constant from one year to the next. The quantity of waste is affected by the farm gate price for the commodity and seasonal conditions that influence quality and yield. Market and weather conditions vary and are difficult to predict especially over the long term. Potential investors have to consider a number of possible scenarios including sourcing vegetable and other organic wastes from other vegetable growers, food processors and other waste generators.

Important considerations for a potential investor in a BSF facility include:

- Is there domestic and/or export market demand for the BSF larvae or the BSF meal? What particular characteristics do buyers require and can these be met? Is demand growing and are there opportunities for new suppliers to enter the market? What barriers to entry exist – are there any regulations governing the establishment of a BSF larvae conversion facility; will financial organisations lend for such a venture; is the product acceptable to the market as a replacement for fishmeal and other protein meals?
- Can harvested BSF larvae that meet market requirements be transported to the refiner efficiently and reliably without loss of condition or value?
- Will sufficient volume of BSFF larvae be produced in the area to attract and sustain establishment of a refining and processing operation or are refining facilities within

[73] Veldkamp, T, van Duinkerken, G, van Huis, A, Iakemond, C M M, Ottevanger, E, Bosch, G and van Boekel, M A J S. 2012 *Insects as a sustainable feed ingredient in pig and poultry diets – a feasibility study*. Report 638. Wageningen UR Livestock Research October.

economic reach of the BSF larvae raising site? Can the refiner accommodate increased BSF larvae supplies?
- Are technical and market information services available and readily accessible?

If these questions cannot be answered satisfactorily then the risk of an investment failing is high.

10.3.2 Fixed costs and equipment

Where daily waste production is relatively low, a suitable option may be to use one or more ProtoPod™ bioconversion units. The ProtoPod is produced by ESR International, the company that manufactures the BioPod which was used in this project for raising the BSF larvae. The ProtoPod was designed for commercial applications whereas the BioPod is for domestic use. A single ProtoPod can handle around 10kgs of organic waste per day. To accommodate the daily post-harvest waste from one hectare of capsicums for example, a vegetable grower would need a bank of 10 ProtoPods. It is estimated that each unit would cost about $400. They need to be housed to ensure that they are protected from direct sunlight and rain. Housing costs to accommodate a bank of 10 ProtoPods could range from $5,000 to $15,000 depending on the type of construction and the facilities included.

Labour requirements for servicing a bank of ProtoPods would be significant as there is little scope for automation or labour use economies with ProtoPods. As the number of bioconversion units increases, labour costs will increase, which reduces the attractiveness of the option. The optimal number of ProtoPods is likely to be less than 10 and probably less than 5. In fact the optimal number with respect to labour could be one unit. If this is the case, for situations where waste exceeds 10 kilograms per day, alternative processing facilities are needed.

Figure 35 - A small-scale ProtoPod operation in Hawaii

Where the supply of waste exceeds 10kg per day, a better option would be to design and construct a conversion facility that can accommodate the quantity of daily waste in one or two units. Such units could be constructed based on recommendations of previous research or a suitable scale system could be commissioned from a company that specialises in BSF bioconversion.

There are a number of overseas companies that can design and supply a complete facility to match the scale of a particular waste stream. For example, Canadian company Enterra has developed and tested at the laboratory, pilot and commercial demonstration scale bioconversion units and hatchery modules which provide a fully controlled, artificial environment optimized for the lifecycle of the black soldier fly[74].In March 2014 Enterra announced that Canadian venture capital firm Avrio had invested $5 million in the company's first commercial-scale pilot facility in Langley, British Columbia[75]. At full capacity the facility will be able to process 54,000 tonnes per year of pre-consumer food waste. This investment was prompted by Metro Vancouver's ban on the disposal of food and other organics into its waste stream by 2015.

As more cities regulate for no waste, the demand for large-scale bioconversion facilities will increase. Organic Value Recovery Solutions LLC (OVRSol) has developed a system that is scalable and adaptable to the waste stream. AgriProtein, a South African company, will commence processing 110 tonnes of organic waste per day at a $3.7 million plant in Stellenbosch, South Africa from October 2014[76]. The company plans to license its technology around the world from 2015. The technology is scalable with small units developed for rural areas in South Africa[77].

A single vegetable grower may not produce sufficient quantities of vegetable waste throughout the year to justify investment in a BSF meal production enterprise. However, individual growers in a local area may set up with ProtoPods or a custom-designed unit to produce the pre-pupae which can be sold to a local refiner for the final stages of meal manufacture. The existence of a large scale refiner is essential to the success of the operations by individual vegetable growers. The refiner would be able to benefit from production and sale of by products such as biodiesel, fertilizer and chitin in addition to the production of BSF meal.

Advantages of a large scale bioconversion system over multiple conversion pods is that economies can be achieved in the use of labour, automation can be integrated into the design and quality control be better managed.

10.3.3 Variable costs

It is not possible to provide specific costs for establishing and operating a BSF larvae production facility due to the nonexistence of commercial operations in Australia. An absence of laboratory feeding trials and pilot trials of BSF larvae in Australia precludes the availability of cost data. A search of the literature revealed very few published studies on costs and returns of using black soldier fly to reduce organic wastes and produce feed inputs suitable for livestock and aquaculture. One study from North Carolina State University analysed costs and returns from a pilot facility designed to process manure from a small-scale piggery using BSF larvae[78]. The authors were able to estimate costs and compare these

[74] Enterra website:http://www.enterrafeed.com/products/
[75] Sourced from: http://www.pehub.com/canada/2014/03/28/avrio-capital-invests-5-mln-in-enterra-feeds-pilot-food-waste-facility/ 18 June 2014
[76] http://www.theguardian.com/environment/2013/oct/04/flies-fish-food-factory-south-africa
[77] http://www.agriprotein.com/
[78] Newton, L, Sheppard, C and Watson, S. 2006. Cost and returns analysis of manure management systems. Technology report: Black Soldier Fly, January. Cited at: http://www.cals.ncsu.edu/waste_mgt/smithfield_projects/phase3report06/pdfs/B.10.pdf on 22 June 2014

with estimates of BSF larvae values. Future research on feeding trials of BSF larvae should include documentation and analysis of the costs of setting up and operating laboratory or pilot facilities to provide an indication of the economic feasibility of using BSF to produce inputs for aquafeed and other livestock feeds.

10.3.4 Aquafeed demand, the price of fishmeal and competition from substitutes

Critical to the economics of using BSF larvae in compound aquafeeds and other livestock feed diets is the price of fishmeal and other fishmeal substitutes. As the price of fishmeal increases relative to the prices received for production from aquaculture, the demand for fishmeal will fall as other protein sources are substituted for fishmeal in aquafeed diets and improvements occur in the efficiency of fishmeal utilisation.

The price of fishmeal is driven by the demand for fish, the growth in aquaculture production, the supply of raw material used in fishmeal production (largely capture fisheries, supplies from which are governed by allowable quotas, and supplies of fish processing waste), the prices of other proteins (e.g., soybean, wheat, rapeseed, and corn gluten), the demand for pig and poultry meat (fishmeal is a primary protein source in the diets of poultry and pigs), energy prices, improvements in feed conversion rates, per capita income and population growth.

Over the last 30 years farmed fish production has increased by at an average annual rate of over 8% in response to the growing demand for fish. The World Bank (2013) expects production from farmed fish to increase to 93 million tonnes by 2030 from 64 million tonnes in 2011[79]. However, over this period the rate of growth of aquaculture production is forecast to decline. The average annual growth rate of aquaculture production in the years 2020 to 2029 is forecast to be less than 2%. According to World Bank forecasts aquaculture is expected to contribute 62% of global food fish production by 2030.

On the demand side, the World Bank forecasts fish consumption to increase from 17.2 kilograms per capita in 2010 to 18.2 kilograms in 2030, with the highest consumption growth expected in regions with the highest per capital income growth (China, India and South-east Asia). An increasing share of fish consumed will be source from aquaculture.

Fishmeal is the single most important source of protein in aquafeed. One of the main drivers to reduce the content of fishmeal in compound aquafeeds has been the rise in the price of fishmeal. The price has risen at an average annual rate of 8.6% in real terms since 2000. Figure 36 demonstrates the growth in the real and nominal price for fishmeal over the last decade. The rising price reflects the increasing cost of energy, El Nino effects on fish catch, diversion of capture fish used for feed to human consumption and increasing demand.

[79] The World Bank. 2013. *Fish to 2030: prospects for fisheries and aquaculture*. World Bank Report No. 83177-GLB. Washington, DC, December.

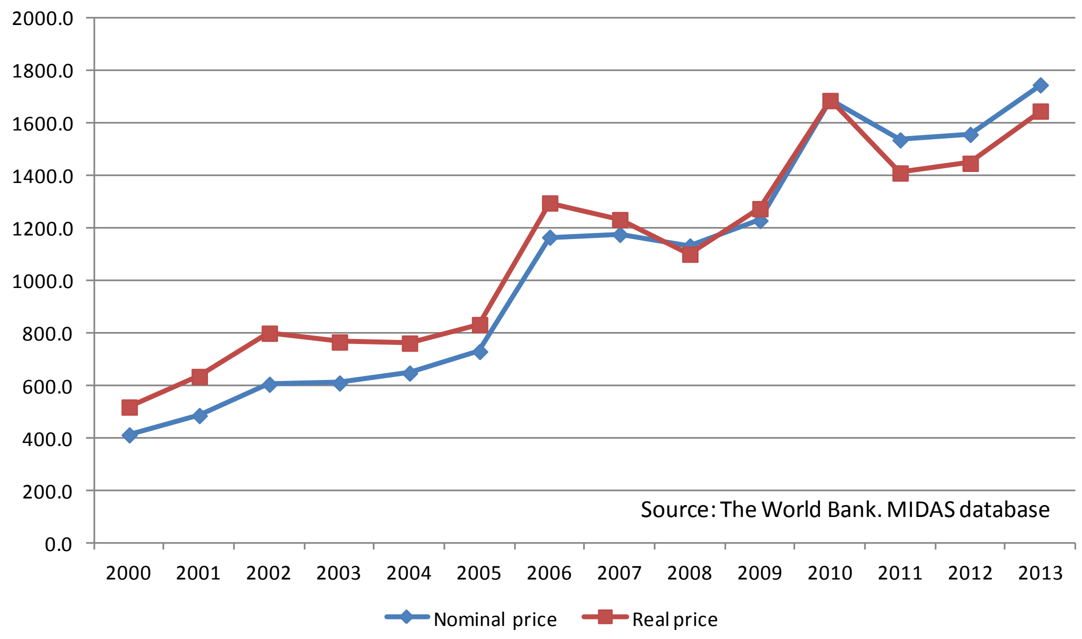

Figure 36 - Trend in wholesale price of fishmeal, 2000 to 2013 (US$/tonne)

Since the early 1990s the proportion of wild fish catch used as fishmeal has declined from 23% (26 million tonnes per year) to 10% (16 million tonnes) in 2012[80]. This trend is expected to continue driven by falling supplies of raw materials especially from capture fisheries, use of more cost-effective fishmeal replacers and improvements in feed use efficiency. Replacers include plant proteins and waste products from fish and terrestrial animals. Feed conversion efficiencies have been improved through selection of improved and better breeds of fish and other aquatic species.

According to Jackson[81] there are limited prospects for increasing the production of fishmeal and fish oil as most of the fisheries that supply the raw material are governed by tightly set and monitored quotas[81]. Tacon et al (FAO 2011) concluded that 'the sustainability of the aquaculture sector is more likely to be linked with the sustained supply of terrestrial animal and plant proteins, oils and carbohydrate sources for aquafeeds' [82]. This is because a significant proportion of aquaculture production is of the non-carnivorous species. Therefore, BSF larvae based meals will need to competitive with plant and animal based proteins as the share of fishmeal in aquafeeds and livestock feeds declines.

Jackson[81] suggested that fishmeal is becoming less of a commodity and more of a strategic ingredient in areas where its unique nutritional properties give the best results and where price is less critical (hatchery and broodstock feeds). Profitable use of fishmeal is likely to be used in high-value and feed-efficient aquaculture products (World Bank 2013). The World Bank forecasts the growth in fishmeal use in global aquaculture for the period 2000 to 2030

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[80] HLPE.2014. Sustainable fisheries and aquaculture for food security and nutrition. A report by the High Level panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome, June.

[81] Jackson, A.2012. 'Fishmeal and fish oil and its role in sustainable aquaculture'. *International Aquafeed*, September-October, pp.18-21.

[82] Tacon,A G J, Hasan, M R and Metian, M. 2011.Demand and supply of feed ingredients for farmed fish and crustaceans: trends and prospects. FAO Fisheries and Aquaculture Technical Paper No. 564. FAO, Rome.

to be 1.7% per year, compared to the average annual growth in fed aquaculture of 3.9%. This is driven by continued improvement in feed conversion efficiency and use of fishmeal replacers. For example, soy meal has increased significantly over the past 20 years as a replacer for fishmeal in aquafood diets.

The HLPE (2014) report on sustainable fisheries and agriculture recommended that 'states and other private and public stakeholders and international actors should put in place appropriate actions to reduce further the use of fish meal and fish oil as feed in aquaculture and livestock production, and should encourage their elimination by the use of alternate sources as well as by the promotion of low trophic level fish (herbivores and omnivores)'. This is particularly relevant to the use of capture fish species that have potential for human consumption, contributing to improvements in food security.

The implications of these supply and demand trends for aquaculture products for BSF larvae production are encouraging. The demand for alternative protein sources to replace fishmeal in compound feeds for aquaculture and terrestrial livestock will continue to rise. However, fishmeal replacers need to be cost competitive, nutritionally appropriate and sustainably sourced. They need to be proven in terms of their acceptability by farmed fish species. Replacers need to maintain or improve fish growth rates and they should be free of harmful health risks. Finally, they need to be affordable and contribute to improving the profitability of aquaculture.

11 Appendix 1 – Nutritional content of fishmeal compared to insect based feeds.

	Unit	Fishmeal	BSF	Mealworm	Superworm	Housefly
Dry weight	%	25	44	39	42	25
Crude protein	% DW	75	42	53	47	50
Crude fibre	% DW	1	7	12	9.3	6
Ash	% DW	14	21	3	2.4	10
Fat	% DW	10	35	39	42	12
Gross energy	MJ/kg DW	22	22	27	25	23
Calcium	g/kg DW	26	76	23	25	5
Phosphorus	g/kg DW	22	9	8	6	16
Potassium	g/kg DW	12	7	9	8	6
Sodium	g/kg DW	11	1.3	0.9	1.1	5
Magnesium	g/kg DW	3	4	2.3	1.2	3.4
Manganese	mg/kg DW	10	246	15	22	91
Zinc	mg/kg DW	99	108	144	83	119
Copper	mg/kg DW		6	21	15	27
Iron	mg/kg DW		1370	89	92	995

12 Appendix 2 – Enterra Feed Product Specifications

Enterra

Renewable Food™
For Animals and Plants

Hermetia illucens—Black Soldier Fly

Enterra Feed produces sustainable ingredients for food production, including high quality protein and fatty acids that are used in animal feed, and a concentrated natural fertilizer used for soil conditioning.

Our unique process deploys the larvae of a common beneficial insect, the Black Soldier Fly, grown in a fully controlled environment using a fixed recipe sourced from clean, traceable streams of pre-consumer waste fruits, vegetables, fish and grains.

Enterra provides:

- high-quality feed products with a consistent nutrient profile
- guaranteed quantities, available through all seasons
- predictable, stable prices

Enterra Feed Corporation
134—887 Great Northern Way
Vancouver, British Columbia
604.639.1628
info@enterrafeed.com

July 2013

Enterra Feed Oil™ Product Specifications

Description:	A lipid material derived from larvae of the Black Soldier Fly (*Hermetia illucens*).
Intended use:	A source of crude fat for use as a feed ingredient in aquaculture, poultry feeds, and other animal feeds, and as a substitute for palm kernel oil and coconut oil.
Chemical Analysis:	Lauric Acid (C12): 58% Palmitic Acid (C16): 9% Myristic Acid (C14): 8% Omega 3: 2.5% Omega 6: 6% Omega 9: 10% Total Oil: 99.1% Free Fatty Acids: 1.8% Unsaponifiable matter: 0.6% Energy: 3700 KJ/100g Vitamin D: 830 IU/100g
Physical Standards:	Colour: yellow-orange Melting Point: 35-40 C Odour: No foreign odours Moisture: <1%
Storage:	The product is to be stored in a cool dry area.

www.enterrafeed.com