1.2 Which Insect Species and Why?

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1.2.1 Introduction

This chapter focuses on describing the common features determining the suitability of insects for small and industrial scale farming, the main insects species currently being produced on a large scale for feed production, as well as other potential candidate species. Natural consumption of insects by animals and which insects are suitable for what animal feed is also discussed.

1.2.2 Common Features of Insects Reared for Animal Feed

Despite the huge diversity of insects, not all are suitable for use in animal feed or large-scale production, and currently research and development of industrial rearing systems for the production of animal and pet feeds is limited to just a few species. The major species produced worldwide include the Dipteran species Black soldier fly (BSF; *Hermetia illucens*) and the Common housefly (HF; *Musca domestica*), the Coleopteran species yellow Mealworm (YM; *Tenebrio molitor*), the Orthopteran crickets, locusts and grasshoppers, (van Huis, 2016). In addition, differences in the legislation surrounding the use of insects in feed also impacts commercialisation efforts; for example current EU legislation only permits certain insect species including BSF, HF, YM , lesser mealworm (LM; *Alphitobius diaperinus*), house cricket (HC; *Acheta domesticus*), banded cricket (BC; *Gryllodes Sigillatus*) and field cricket (FC; *Gryllus* spp.), which have been reared on materials of vegetal origin in aquaculture feed, while for instance manure or catering waste is prohibited due to risks of pathogen transmission and toxin accumulation (*EU*, 2017). Meanwhile, there are fewer restrictions in Asia, Africa, and America in terms of insect species and rearing substrates. For instance, BSF larvae is permitted in chicken feed in Canada (Sogari *et al.*, 2019).

Species currently farmed and under commercial development for industrial scale production are characterised by short life cycles (Figure 1), high feed conversion efficiency, amenability to mass rearing and their ability to grow at high densities on low value 'wastes' (Makkar *et al.*, 2014). Key also is comparability of nutrient profiles to fishmeal and soymeal that make insects and processed products suitable for incorporation into compound feed although, like other feed ingredients, insect derived products must not contain harmful levels of microbial or chemical contaminants. Insects such as BSF and HF are prone to bioaccumulation of heavy metals such as cadmium, lead, copper and zinc (Diener, Zurbrügg and Tockner, 2015; Gao *et al.*, 2019). To avoid bioaccumulation in the food chain, the quality of the rearing substrates must be monitored closely.

Different animal species vary in their nutritional requirements, in terms of amino acid profile, lipid content and micronutrients, and these often change depending on the growth stage of the animal (Kim *et al.*, 2019). Whilst insects can be fed live or dried in small scale farming scenarios, at industrial scale insect products must be formulated alongside other raw materials and additives in compound feeds. The incorporation of insects into compound feed should not compromise and should ideally improve animal performance as compared to traditional feeds. Insect amino acid profiles are suitable for monogastric animals and fish, prawns and shrimp as they require high levels of protein and, unlike ruminants, are unable to synthesise all the essential amino acids (Riddick, 2013; Makkar *et al.*, 2014; Henry *et al.*, 2015; Cummins *et al.*, 2017; Digiacomo and Leury, 2019). On the contrary, soybean meal often requires amino acid supplements when used in feed for monogastric animals (Parolini, Ganzaroli and Bacenetti, 2020).

Insect rearing involves cultivating the species from eggs to larvae (or nymphs) to adults. Usually, an adult breeding culture is maintained separately from larval production to obtain eggs (Makkar *et al.*, 2014). Small-holder farmers in Africa do however use natural oviposition systems, for example by placing crop residues on small termite nests to increase termite populations, or attracting flies for maggot production by exposing organic waste substrates (Kenis *et al.*, 2014). For farming to be feasible, the insect must be reared easily and at an economically and environmentally sustainable cost. In lower income countries, for example in the Asia Pacific region and Africa, where labour is relatively cheap, smaller scale farming systems are cheap to establish, and typically involve single-cage farming to supply subsistence products for individual farmers (Kenis *et al.*, 2014; Yen, 2015). By contrast, larger scale and increasingly automated systems are seen as essential in higher income countries where labour costs are higher and feed supply chains may be more centralised. Large scale rearing requires optimisation of the rearing conditions (temperature, humidity and rearing substrates) to shorten developmental times allowing more generations per year, increased biomass conversion efficiencies (i.e. waste to insect biomass) and thereby increased productivity (Makkar *et al.*, 2014).

1.2.3 Insects Species Reared at Large Scale

Black Soldier Flies

The Dipteran species BSF, *Hermetia illucens*, is native to America and now widespread in tropical and warmer temperate zones between 45°N and 40°S (Diclaro and Kaufman, 2009). Dense populations are commonly found growing in the manure of poultry, pigs and cattle and other organic wastes, for example rotting fruits and vegetables (van Huis *et al.*, 2013). BSF larvae (BSFL) are high in protein and fat, with approximately 35–57% crude protein and 35% crude lipid (dry wt.) (Veldkamp *et al.*, 2012). Their lauric acid levels are high, ranging from 16-70% of the total fat content (Liu *et al.*, 2017). BSFL are thus able to efficiently convert a wide range of 'waste' streams into high-value protein and fat while reducing the mass, moisture and odours of the waste (Makkar *et al.*, 2014).

BSF tolerate a range of rearing conditions, although temperature and diet quality have a large impact on the life cycle length. Ideal rearing conditions for larvae are between 29–31°C with a humidity of 50–70% (Makkar *et al.*, 2014) whereas adults can be reared between 27.5–37.5°C (Veldkamp *et al.*, 2012). Adult flies are reared separately and each female oviposits once and can lay 206–1088 eggs (Tomberlin *et al.*, 2002; Samayoa *et al.*, 2016). BSF eggs hatch 2-4 days after oviposition, and the larval stage may last 14 days to 4 months, pupation lasts between 14 days and 5 months and the adult female flies mate two days after they emerge (Diclaro and Kaufman, 2009; Makkar *et al.*, 2014). In nature, larvae feed within the moist, organic substrate and subsequently migrate to a dry site to pupate (Liu *et al.,* 2017). At the point of harvest, larvae weigh up to 220 mg (Tran *et al.*, 2015). Their migratory behaviour can be exploited during rearing, as larvae self-harvest by migrating into a collection vessel as they seek to find a location to pupate (Makkar *et al.*, 2014).

As adult BSF do not feed, they are not vectors of disease and this is an important facet of feed and food safety (van Huis *et al.*, 2013). The choice of substrate affects the duration of the rearing cycle the sustainability, the performance of the flies, as well as their final nutritional content (Gold *et al*., 2020).

Common housefly

HF, *Musca domestica,* is globally the most common Dipteran species being most frequently found in tropical environments on manure and decaying organic waste. The flies require a humid and warm environment, ideally over 25°C (Diehl *et al.*, 2014). Their life cycle is short, with eggs hatching 8-12 hours post oviposition, the larval stage lasting 4-13 days, but typically 5 days at optimal conditions, and pupation lasts 4-5 days (Sanchez-Arroyo and Capinera, 1998). As for BSFL, they grow in dense populations and the length of the cycle is highly dependent upon rearing conditions. The combined larval and pupal stage can be reduced from 10 to 6 days under optimised conditions at 32–38 °C, 50–70% humidity and a substrate of decaying organic matter (Diehl *et al.*, 2014; Makkar *et al.*, 2014). The number of eggs laid per female can also be increased from 500-600 up to 2000 by optimising rearing conditions (Heuzé and Tran, 2015). HF larvae develop more quickly than BSFL, but they are much smaller with pupae weighing approximately 18 mg compared to BSF pupae of 153–156 mg (Barnard and Geden, 1993; Shumo *et al.*, 2019). As compared to BSF, HF are easier to rear and they tolerate colder temperatures and drier climates. HF larvae typically have higher protein contents than BSFL, at 43–68% crude protein (dry wt.), and crude lipid ranges from 4–32% (dry wt.) (Veldkamp *et al.*, 2012).

Houseflies are adapted to feeding on bacteria and fungi and smaller particles than BSF, and whilst they are most commonly reared on animal manures they can feed on vegetal wastes and desiccated *E. coli* or yeasts (Levinson, 1960; Haupt and Busvine, 1968, van Huis *et al.,* 2020). A major drawback for large-scale HF rearing is that the adults feed and are known to transmit over 100 infectious diseases (van Huis *et al.,* 2020). Unlike adult BSF, adult HF are drawn to human and animal habitats. The larvae themselves may harbour rearing substrate microbes and this raises potential issues for safe use as animal feed especially when, as occurs in rural Africa, larvae are fed live to poultry and fish (Awoniyi, 2007; Kenis *et al.*, 2014). Gut clearance and processing methods such as heat treatment, commonly used for other feed ingredients have, however, been shown to mitigate potential microbiological risks (Hall *et al.*, 2018).

Mealworm

Larvae of the Tenebrionidae beetle species *Tenebrio molitor* and *Tenebrio obscurus* are commonly known as Yellow and mini mealworm, respectively. The beetles are native to Europe, but are found worldwide (Makkar *et al.,* 2014). Industrial scale production of mealworms is already established, mainly for wild bird, pet and zoo animal feed, as they are relatively easy to rear and have good nutritional value, suitable for use in for instance poultry feed (van Huis *et al.,* 2013). The LM, *Alphitobius diapernius*, and the SW, *Zophobas morio,* are reared for reptile and amphibian pet feed (van Huis, 2020). Mealworm larvae typically contain 44–69% (dry wt.) crude protein and 23-47% (dry wt.) crude lipid (Veldkamp *et al.*, 2012). Additionally, they provide good sources of zinc and magnesium, whilst being relatively low in calcium (Grau *et al.,* 2017).

The larvae are sold live, dried, canned or as a powder for feed (Veldkamp *et al.*, 2012). Ideal rearing conditions are colder than for the flies, at 18-25 °C and life cycle duration typically lasts 250–360 days depending on rearing conditions (Makkar *et al.,* 2014). The egg stage lasts 10–12 days, and larval maturation normally takes 3-4 months. They pupate for 7–9 days, and adult beetles live for 2–3 months. Mealworms are omnivorous, and like BSF and HF, can be reared on organic plant or animal wastes (van Huis *et al.,* 2013). Traditionally, their commercial diet has however consisted of cereal bran or flour supplemented with protein (Makkar *et al.,* 2014). As for HF, there is a risk of microbial transmission when using mealworms in feed, but microbial load can be significantly reduced by heating or bleaching the larvae (Grau *et al.,* 2017).

Crickets, locusts and grasshoppers

More than 20,000 insect species belong to the order Orthoptera, including crickets, locusts and grasshoppers (Ayieko *et al.,* 2015). These are generally edible, and many are commonly consumed by humans in Africa, South America and Asia (van Huis *et al.,* 2013). Locusts, crickets and grasshoppers have typically been harvested from the wild, where they feed on grass, crops and leaves, but domestication is possible (van Huis *et al.,* 2013). For instance, long-horned grasshoppers may be reared in netted enclosures (Ayieko *et al.*, 2015) and grasshopper rearing at industrial scale is being developed for use in feed in South East Asia.

Crickets, locusts and grasshoppers have three lifestages: eggs, wing-less nymphs and adults (Ayieko *et al.*, 2015). In nature, females oviposit in soil, and lay 'pods' containing dozens of eggs during the winter, these hatching in warmer spring temperatures (Ayieko *et al.*, 2015). The maturation time of nymphs is highly dependent on the species, and rearing temperature. Adults become sexually mature after a few weeks. In cold climates, the egg-stage may last up to 9 months, and the nymph and adult stage lasts up to 3 months.

Commercial rearing of house crickets (*Acheta domesticus*) is optimal at 30 °C and 50-70 % humidity, under these conditions a full life cycle can be completed in 8 weeks (Ayieko *et al.*, 2015). In comparison, at 18 °C the life cycle lasts up to 8 months. Locusts, crickets, and grasshoppers generally require a moist, dark place to oviposit, a diet consisting of leaves, alternatively supplemented with wheat germ, vegetables, fruit or in some cases chicken mash, and an available water source.

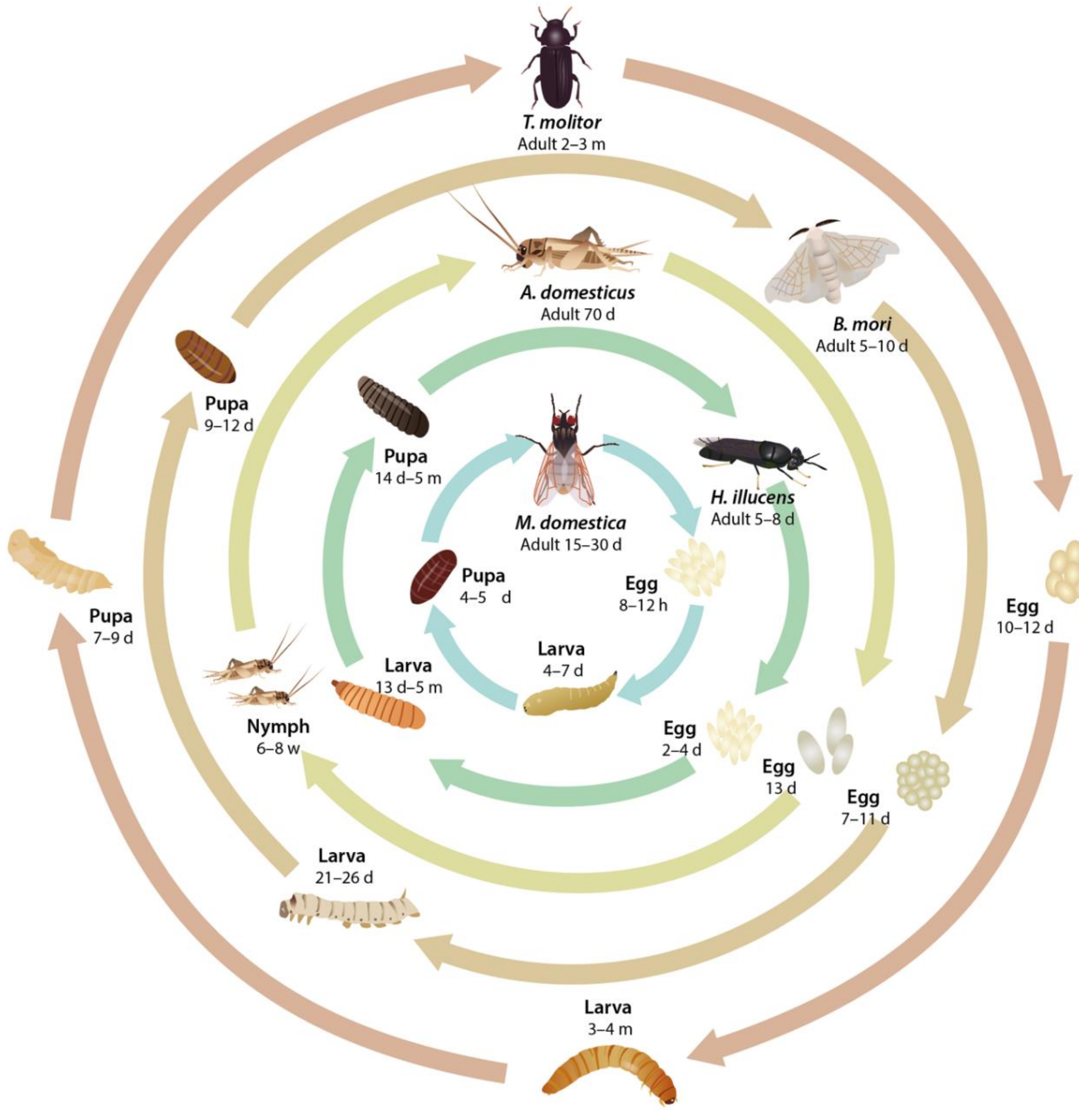

Figure 1: Insect life cycles. The life stages of commonly domesticated insects shown, with the common housefly in the centre, followed by the black soldier fly, the house cricket, the silk moth and mealworm. h = hours, d = days, w = weeks and m = months.

1.2.4 Other insect species as potential candidates

Silkworms

The Lepidopteran silkworm, *Bombyx mori,* was domesticated approximately 5,000 years ago due to its production of valuable silk (Xiang *et al.*, 2018). Silk is derived from the raw silk cocoons produced when the moths pupate, and this process yields large amounts of spent silkworm pupae (Patil *et al.,* 2013). Silkworm pupae are consumed by humans in silk producing countries (China, India and Thailand) and contain approximately 60% crude protein and 25% fat on a dry wt. basis (Makkar *et al.*, 2014). The high protein level makes them good candidates for use in animal feed, especially when processed to remove the oil. The environmental impact of silk production may be reduced by utilising this major by-product (Patil *et al.*, 2013; Sheikh *et al.*, 2018).

The silkworm moth has four life stages: egg, larvae, pupae and adult lasting approx. 7–11, 21–26, 9–12 and 5–10 days, respectively (Gurjar *et al.,* 2018). The complete life cycle lasts between 6 and 9 weeks. Females begin oviposition 5.5 to 8.5 hours after emergence, and they lay approximately 350 eggs in their lifetime (Diehl *et al.,* 2014). Industrial rearing of silkworms is well-established. The environmental requirements for silkworm rearing are 24–27 °C and 70–90% humidity (Krishnaswami, 1978). Silkworms are typically fed with leaves (mulberry leaves for *B. mori*), and their growth and development depends on the quality of their diet (Krishnaswami, 1978). It is also important that they are given sufficient space, as their growth and fecundity is reduced if the density is too high (Krishnaswami, 1978). The need for relatively low rearing densities and preference for a relatively expensive diet of mulberry leaves reduces the suitability of this species for large scale rearing for animal feed (Diehl *et al.,* 2014).

Termites

The Isopteran insects termites, in particular *Macrotermes* species, constitute 3% of global insect consumption by humans (Anankware *et al.*, 2015). These are typically harvested from the wild, for example by beating the ground around the termite hills, which forces them to emerge, or by 'fishing' them out of their nests by getting them to bite onto a stick or leaf (van Huis *et al.*, 2013). The insects are rich in protein, fats and micronutrients, thus can function as a valuable supplement in the diet (Adepoju, 2020) but are also used as fish bait in Zambia (Silow, 1983) and are used in poultry feed in West Africa (Kenis and Hien, 2014). A 50% replacement of fishmeal with termite meal is suitable in the diet of the Catfish *Heterobranchus longifilis* (Sogbesan and Ugwumba, 2008). Large-scale production of termites is not generally considered sustainable due to the difficulty of rearing and their high levels of methane production, a by-product of the symbiosis with the bacteria present in termite (Anankware *et al.*, 2015).

Cockroaches

Blattodean species include the cockroaches, which are known for being resilient, adaptable to a range of environmental conditions and quick population growth (Diehl *et al.*, 2014). For instance, the Madagascar cockroach *Gromphadorhina portentosa* is reared at temperatures 23–26°C and 30% humidity, at which nymphs mature in 3 months (de Carvalho *et al.*, 2019). Meanwhile, the death's head cockroach *Blaberus craniifer* is reared at 25–30°C and 65-80% humidity (Diehl *et al.*, 2014). Vegetable and fruit waste substrates can be used for cockroach rearing. *G. portentosa* contains approximately 67% (dry wt.) crude protein and cockroach meal has been found a suitable protein source for cockatiels when included in the diet at 6.6% (de Carvalho *et al.*, 2019). Potential issues with industrial scale rearing and commercial use of cockroaches is their methane production and potential to transmit pathogens such as *E. coli* and *Salmonella* species (Diehl *et al.*, 2014).

Mopane worm

Imbrasia belina, a lepidopteran moth native to southern Africa, is an important protein source for local populations (Madibela *et al.*, 2008; Okezie *et al.*, 2010). The larvae have high nutritional content with 47–56% crude protein and 16–18% crude fat (dry wt.), and an amino acid profile comparable to fishmeal and soymeal (Makhado *et al.*, 2014). Currently, worms are wild harvested from Mopane trees in Botswana and sold locally, or exported to South Africa for selling as human food or processing into livestock feed (Madibela *et al.*, 2007). Studies on the suitability of mopane worms in feed are limited.

1.2.5 Which Insect for Which Animal?

Insects constitute a natural part of the diet for many animals and most particularly birds and fish (van Huis *et al.,* 2013). Incorporation of these insects in the diet of domesticated animals (as depicted in Figure 2) therefore seems appropriate, as they are in the main evolutionarily adapted to feed on insects. Pigs are omnivores which naturally exhibit foraging behaviour in the wild consuming mainly plant materials such as leaves and fruits, but also fish and invertebrates including beetles, earthworms and insect larvae (Jakobsen *et al.*, 2015). Wild birds and free-range poultry also naturally feed on soil borne insect larvae and worms (Clark and Gage, 1996). Both freshwater and saltwater fish consume insects, especially during the juvenile lifestages. Examples of extensive consumption include Catfish species such as the African Catfish *Clarias gariepinus* and the Common Catfish *Ameiurus melas* which consume insects, and the Atlantic Salmon *Salmo salar* which feeds on aquatic insects (Henry *et al.*, 2015).

Although mass-rearing for feed is relatively new, insects have been reared for exotic pet and zoo animal feed for decades (van Huis *et al.,* 2013). Mealworms and crickets are the most common species, and are reared in Asia, North America, and Europe. Over 100 tonnes of YM are produced annually in China, and there is a large industry for rearing the YM, the LM and the SW in the Netherlands for reptile, avian and fish food (Zhang *et al.,* 2008; van Huis *et al.,* 2013). Mealworms can be fed to cats and amphibians too. Crickets are also extensively used, and billions are sold live in America per year to pet stores for reptiles and fish (Weissman *et al.*, 2012). Crickets have also been found suitable as a potential ingredient in dog food (Jarett *et al.*, 2019). In 2019, the pet food brand In Yora Pet Foods launched a dog food where 40% of the protein comes from BSFL.

Insects differ in their amino acid profiles, lipid content, crude protein and micronutrients. Most insects currently reared at scale, flies and mealworms in particular, have been shown to have a suitable amino acid profile for feeding to monogastric animals, fish, prawns and shrimp (reviewed by Veldkamp *et al.* 2012; Makkar *et al.* 2014; Anankware *et al.* 2015; Henry *et al.* 2015; Sheikh *et al.* 2018; DiGiacomo *et al.* 2019). The nutritional contents of insect vary depending on their life stage, for example the chitin content usually increases in pupae and adult insects compared to larvae, and each insect require specific processing and preparation (Halloran *et al.*, 2018). Some insects, such as mealworms may be fed live, while others are dried, roasted, chopped, defatted, ground or processed to improve chitin digestibility (Henry *et al.*, 2015). Ruminant nutritional requirements are met by both digested feed protein and protein provided by symbiotic rumen microbes, and as they are generally are fed on low-protein diets, insects have not been widely considered for use in ruminant feed (Abbasi *et al.*, 2018).

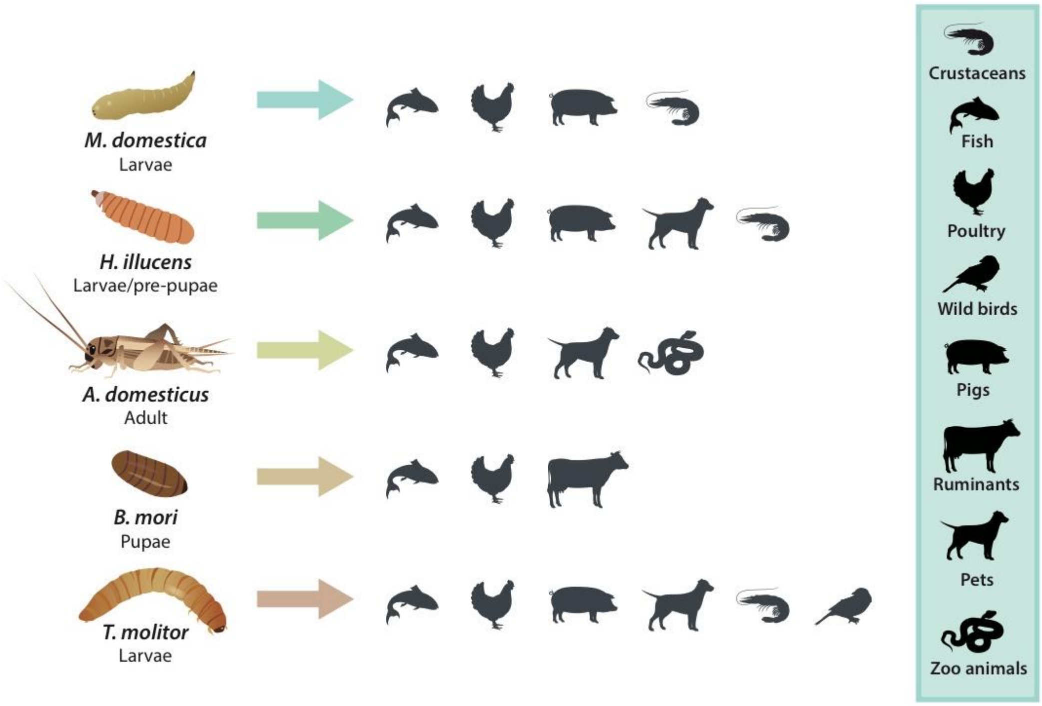

Figure 2: Which insect for which animal feed? Depicting suitability for inclusion of HFL, BSFL and pre-pupae, cricket adults, silkworm pupae and mealworm in the diets of crustaceans, fish, poultry, wild birds, pigs, ruminants, pets and exotic/zoo animals.

1.2.6 Conclusion

In the coming years, further animal feeding trials, ongoing optimisation of industrial rearing systems, and perhaps an expansion of the number of farmable species will help us to realise the potential for the adoption of insects and insect products for animal feed. Historical use together with technology advances, evidence based legislative changes and consumer perception are likely to collectively drive the expansion of production outputs to different extents across distinct geographical locations. Overall, there seems little doubt that insect-based feeds will become increasingly important as the global demand for animal feed, and particularly animal protein, rises.

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