State-of-the-art on use of insects as animal feed

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Abstract

A 60-70% increase in consumption of animal products is expected by 2050. This increase in the consumption will demand enormous resources, the feed being the most challenging because of the limited availability of natural resources, ongoing climatic changes and food-feed-fuel competition. The costs of conventional feed resources such as soymeal and fishmeal are very high and moreover their availability in the future will be limited. Insect rearing could be a part of the solutions. Although some studies have been conducted on evaluation of insects, insect larvae or insect meals as an ingredient in the diets of some animal species, this field is in infancy. Here we collate, synthesize and discuss the available information on five major insect species studied with respect to evaluation of their products as animal feed. The nutritional quality of black soldier fly larvae, the house fly maggots, mealworm, locusts-grasshoppers-crickets, and silkworm meal and their use as a replacement of soymeal and fishmeal in the diets of poultry, pigs, fish species and ruminants are discussed. The crude protein contents of these alternate resources are high: 42 to 63% and so are the lipid contents (up to 36% oil), which could possibly be extracted and used for various applications including biodiesel production. Unsaturated fatty acid concentrations are high in housefly maggot meal, mealworm and house cricket (60-70%), while their concentrations in black soldier fly larvae are lowest (19-37%). The studies have confirmed that palatability of these alternate feeds to animals is good and they can replace 25 to 100% of soymeal or fishmeal depending on the animal species. Except silkworm meal other insect meals are deficient in methionine and lysine and their supplementation in the diet can enhance both the performance of the animals and the soymeal and fishmeal replacement rates. Most insect meals are deficient in Ca and its supplementation in the diet is also required, especially for growing animals and laying hens. The levels of Ca and fatty acids in insect meals can be enhanced by manipulation of the substrate on which insects are reared. The paper also presents future areas of research. The information synthesized is expected to open new avenues for a large scale use of insect products as animal feed.

Key words: insect meals; insect larvae; livestock; monogastrics; ruminants; aquaculture

1 Introduction

Insects have been a part of the human diet for centuries and are currently consumed by humans in many parts of Asia, Latin America and Africa. These are considered to supplement diets of approximately 2 billion people. Due to the current food insecurity situation prevailing in many developing countries and future challenges of feeding over 9 billion people in 2050, lately these have received wide attention as a potential alternate major source of proteins. As a result of increasing incomes, urbanization, environment and nutritional concerns and other anthropogenic pressures, the global food system is undergoing a profound change. There has been a major shift to diets with increased consumption of animal products, and this change is likely to continue in the coming decades. The demand for meat and milk is expected to be 58% and 70% higher in 2050 than their levels in 2010 and a large part of this increase will originate from developing countries (FAO, 2011).

The livestock production is resource hungry: for example it occupies 30% of the world's ice-free surface or 75% of all agricultural land (including crop and pasture land) and consume 8% of global human water use, mainly for the irrigation of feed crops (FAO, 2009; Foley et al., 2011). In addition, the livestock sector contributes approximately 14.5% of all anthropogenic greenhouse gas (GHG) emissions (7.1

Gigatonnes of CO_2-equivalent per year) (Gerber et al., 2013) and animal products generally have a much higher water footprint than plant-based foods (Mekonnen and Hoekstra, 2012). As a result of huge demand for animal products, enormous need of resources including feeds to produce them will ensue. Fuel-feed-food competition is expected to further exacerbate the situation. A quest for novel feed resources is a must.

Insect rearing could be one of the ways to enhance food and feed security (van Huis et al*.,* 2013). They grow and reproduce easily, have high feed conversion efficiency (since they are cold blooded) and can be reared on bio-waste streams. One kg of insect biomass can be produced from on average 2 kg of feed biomass (Collavo et al*.,* 2005). Insects can feed on waste biomass and can transform this into high value food and feed resource. A desk study (Veldkamp et al*.,* 2012) has demonstrated that it is technically feasible to produce insects on a large scale and to use them as alternative sustainable protein rich ingredient in pig and poultry diets, particularly if they are reared on substrates of bio-waste and organic side streams. This paper presents current status on five major groups of insects (black soldier fly, the house fly, mealworm beetles, locusts-grasshoppers-crickets, and silkworm) with regard to their distribution, rearing, environmental impact, nutritional attributes of the insects and insect meal and their use as a component in the diets of ruminants, pigs, poultry (both broiler and laying hen) and fish species, potential constraints, if any in using them as alternative feed resources and future research areas.

2 Black soldier fly larvae (Hermetia illucens)

The black soldier fly (*Hermetia illucens* Linnaeus 1758) is a fly (Diptera) of the Stratiomyidae family. It is native from the tropical, subtropical and warm temperate zones of America. The development of international transportation since the 1940s resulted in its naturalization in many regions of the world (Leclercq, 1997). It is now widespread in tropical and warmer temperate regions between about 45°N and 40°S (Diener et al., 2011). The adult fly is black, wasp-like and 15-20 mm long (Hardouin and

Mahoux, 2003). The larvae can reach up to 27 mm in length and 6 mm in width and weigh up to 220 mg in their last larval stage. They have a dull, whitish color (Diclaro and Kaufman, 2009). The larvae can feed quickly, from 25 to 500 mg of fresh matter/larva/day, and on a wide range of decaying organic materials, such as rotting fruits and vegetables, coffee bean pulp, distillers grains, fish offal and particularly animal manure and human excreta (Hardouin and Mahoux, 2003; Diener et al., 2011; van Huis et al., 2013). In ideal conditions, larvae become mature in 2 months, but the larval stage can last up to 4 months when not enough feed is available (Hardouin and Mahoux, 2003). At the end of the larval stage (prepupa), the larva empties its digestive tract and stops feeding and moving (Hardouin and Mahoux, 2003). The prepupae then migrate in search of a dry and protected pupation site (Diener et al., 2011). The duration of the pupal stage is about 14 days but can be extremely variable and last up to 5 months (Hardouin and Mahoux, 2003). The females mate two days after emerging and oviposit into dry cracks and crevices adjacent to a feed source (Diener et al., 2011). The adults do not feed and rely on the fats stored from the larval stage (Diclaro and Kaufman, 2009).

Rearing *H. illucens* has been proposed since the 1990s as an efficient way to dispose of organic wastes by converting them into a protein-rich and fat-rich biomass suitable for various purposes, including animal feeding for all livestock species, biodiesel and chitin production (Diener et al., 2011; van Huis et al., 2013). The black soldier fly is an extremely resistant species capable of dealing with demanding environmental conditions, such as drought, food shortage or oxygen deficiency (Diener et al., 2011). One major advantage of *H. illucens* over other insect species used for biomass production is that the adult does not feed and therefore does not require particular care and is not a potential carrier of diseases. The larvae are sold for pets and fish bait, and they can be easily dried for longer storage (Leclercq, 1997; Veldkamp et al., 2012). A disadvantage of the black soldier fly for biodegradation is that it requires a warm environment, which may be difficult or energy-consuming to sustain in temperate climates. Also, the duration of the life cycle ranges between several weeks to several months, depending on temperatures and the quality and quantity of the diet (Veldkamp et al., 2012). In aquaculture, using feeds based on black soldier fly larvae open additional marketing opportunities for farmers as some customers are opposed to the use of fishmeal in aquaculture feeds (Tiu, 2012). The substantial increase in the market price of both soymeal and fishmeal in the last decade may help to make this protein source economically viable for animal feeding.

Several methods for rearing black soldier flies on substrates such as pig manure (Newton et al., 2005), poultry manure (Sheppard et al., 1994) and food wastes (Barry, 2004) have been designed. Rearing facilities use the migrating behaviour of the prepupae for self-collection: larvae climb up a ramp out of a rimmed container to eventually end in a collecting vessel attached to the end of the ramp (Diener et al., 2011). Optimum conditions include a narrow range of temperature and humidity, as well as a range of suitable levels of texture, viscosity, and moisture content of the diet. Temperature should be maintained between 29 to 31ºC though larger ranges may be feasible. Relative humidity should fall between 50 and 70%. Higher relative humidity makes the diet too wet and the diet should have enough structure, otherwise the larvae may have a difficult time crawling on it, consuming it and getting adequate oxygen supply (Barry, 2004).

It is also necessary to maintain a year-round breeding adult colony in a greenhouse with access to full natural light throughout the year. The greenhouse must be a minimum of 66 m^3 to allow for the aerial mating process (Barry, 2004). Ranges of optimal temperatures for mating and oviposition of 24-40°C or 27.5-37.5°C have been reported (Sheppard et al., 2002). Wide ranges of relative humidity are tolerated: 30-90% (Sheppard et al., 2002) or 50-90% (Barry, 2004). The greenhouse will need a container with an attractive and moist medium to attract egg-laying female adults (Barry, 2004).

Dense population of larvae can convert large volumes of organic waste into valuable biomass (van Huis et al., 2013). These can be used commercially to solve a number of environmental problems associated with manure and other organic wastes. For instance, larvae can reduce laying hen or pig manure accumulation by 50% or more without using extra resources including energy (Sheppard et al., 1994; Barry, 2004; Newton et al., 2005). Reduction values of 65-75% in household waste have been observed in field trials in Costa Rica (Diener et al., 2011). In confined bovine facilities, the larvae were found to reduce available phosphorous by 61-70% and nitrogen by 30-50% (Newton et al., 2008).

Adult black soldier flies are not attracted to human habitats or foods and are not considered a nuisance (van Huis et al., 2013). Black soldier fly larvae process organic waste very quickly, restraining bacterial growth and thereby reducing production of bad odour to a minimum. Moreover, the larvae species aerates and dries the manure, reducing odours (van Huis et al., 2013). Black soldier fly larvae are a competitor to housefly (*Musca domestica*) larvae, as they make manure more liquid and thus less suitable for housefly larvae. Their presence is also believed to inhibit oviposition by the housefly. For instance, they have been shown to reduce the housefly population of pig or poultry manure by 94-100%. As a result, they can help to control housefly populations in livestock farms and in households with poor sanitation, thereby improving the health status of animals and people since housefly is a major vector of diseases (Sheppard et al., 1994; Newton et al., 2005).

Unlike other fly species, *H. illucens* is not a disease vector: not only the eggs are never laid on decaying organic material, but, since the adult fly cannot eat due to its lack of functioning mouthparts, it does not come in contact with unsanitary wastes (van Huis et al., 2013). Additionally, the larvae modify the microflora of manure, potentially reducing harmful bacteria such as *Escherichia coli* 0157:H7 and *Salmonella enterica* (Erickson et al., 2004). It has been suggested that the larvae contain natural antibiotics (Newton et al., 2008).

2.1 Chemical constituents

Black soldier fly larvae (also called as: black soldier fly larvae meal, black soldier fly prepupae meal, soldier fly prepupae meal, black soldier fly maggot meal) are used live, chopped, or dried and ground.

There have been attempts to create a defatted meal by cutting the larvae to enable the leakage of intracellular fat and then transferring the material to a tincture press (Kroeckel et al., 2012).

Black soldier fly larvae are a high-value feed source, rich in protein and fat. They contain about 40-44% crude protein (CP) (Table 1). The amount of fat is extremely variable and depends on the type of diet: reported values are 15-25% for larvae fed on poultry manure (Arango Gutierrez et al., 2004), 28% on swine manure (Newton et al., 2005), 35% on cattle manure (Newton et al., 1977) and 42-49% on oil-rich food waste (Barry, 2004). They tend to contain less CP and more lipids than housefly (*Musca domestica*) maggots. Ash content is relatively high but variable, from 11 to 28% dry matter (DM). The larvae are rich in Ca (5-8% DM) and P (0.6-1.5% DM) (Newton et al., 1977; Arango Gutierrez et al., 2004; St-Hilaire et al., 2007b; Yu et al., 2009) (Table 2). The lysine is particularly rich (6-8% of the CP) (Table 3). The DM content of fresh larvae is quite high, in the 35-45% range, which makes them easier and less costly to dehydrate than other fresh byproducts (Newton et al., 2008).

Table 1. Chemical composition of black soldier fly larvae

Crude protein (% in DM), n=5	**Crude fibre (% in DM), n=1**	**Ether extract (% in DM), n=5**	**Ash (% in DM), n=5**	**Gross energy (MJ/kg DM)**
42,1 ± 1.0 (41.1, 43.6)	7.0	26.0 ± 8.3 (15.0, 34.8)	20.6 ± 6.0 (14.6, 28.4)	22.1

DM, dry matter; values in parentheses are minimum and maximum values; values are mean ± standard deviation

Sources : Arango Gutierrez et al. (2004); Newton et al. (1977); St-Hilaire et al. (2007).

Table 2. Mineral content of black soldier fly larvae (all values in g/kg DM except Mn, Zn, and Cu which are in mg/kg DM)

Ca	**P**	**K**	**Na**	**Mg**	**Fe**	**Mn**	**Zn**	**Cu**
75.6 ± 17.1 (50.0, 86.3)	9.0 ± 4.0 (6.4, 15.0)	6.90	1.30	3.90	1.37	246.0	108.0	6.0

For Ca and P, n=4 and for the rest n=1; values are mean ± standard deviation; DM, dry matter; values in parentheses are minimum and maximum values

Sources : Arango Gutierrez et al. (2004); Newton et al. (1977).

The fatty acid composition of the larvae depends on the fatty acid composition of the diet. The lipids of larvae fed on cow manure contained 21% of lauric acid, 16% of palmitic acid, 32% of oleic acid and 0.2% of omega-3 fatty acids, while these proportions were respectively 43%, 11%, 12% and 3% for larvae fed 50% fish offal and 50% cow manure. Total lipid content also increased from 21% to 30% DM. Feeding black soldier fly larvae with a diet made of wastes containing desirable omega-3 fatty acids is therefore a way to enrich the final biomass (St-Hilaire et al., 2007b). In a recent study, oil from black soldier larvae larvae has also been used to produce biodiesel (Zheng et al., 2012). Furthermore, a number of other insects have also been studied as a source of oil for biodiesel production (Pinzi et al., 2014).

Table 3. Amino acid composition of black soldier fly larvae

Amino acids	**g/16 g Nitrogen**
Alanine(n=4)	7.7 ± 0.8 (6.9, 8.8)
Arginine (n=4)	5.6 ± 0.3 (5.3, 6.1)
Aspartic acid (n=4)	11.0 ± 1.8 (8.5, 12.5)
Cystine (n=1)	0.1
Methionine (n=4)	2.1 ± 0.3 (1.7, 2.4)
Lysine (n=4)	6.6 ± 0.9 (6.0, 8.0)
Isoleucine (n=4)	5.1 ± 0.5 (4.7, 5.6)
Leucine (n=4)	7.9 ± 0.6 (7.1, 8.4)
Phenylalanine (n=4)	5.2 ± 0.4 (4.6, 5.6)
Threonine (n=4)	3.7 ± 1.7 (1.3, 4.8)
Tryptophan (n=1)	0.5
Glutamic acid (n=4)	10.9 ± 2.4 (8.7, 13.5)
Histidine (n=4)	3.0 ± 1.0 (2.3, 4.5)
Proline (n=2)	6.6 (5.5, 7.7)
Serine (n=4)	3.1 ± 1.9 (0.3, 4.2)
Tyrosine (n=4)	6.9 ± 0.7 (6.0, 7.7)
Valine (n=4)	8.2 ± 1.4 (6.4, 9.1)

Values are mean ± standard deviation

Sources : Newton et al. (1977); Sealey et al. (2011); St-Hilaire et al. (2007).

2.2 Nutritional value for different animal species

2.2.1 Livestock

Pigs. Black soldier larvae meal was found to be a suitable ingredient in growing pig diets, being especially valuable for its amino acid, lipid and Ca contents. However, its relative deficiency in methionine + cystine and threonine requires the inclusion of those amino acids for the preparation of balanced diets. The ash content of the meal is also high and this requires attention. The diets containing the larvae meal were as palatable as a soymeal based diet (Newton et al., 1977).

Dried black soldier fly prepupae meal was fed to early weaned pigs as a replacement (0, 50, or 100%) for dried plasma (meal in the diet: 0% during phase 1, 2.5% during phase 2, and 5% during phase 3), with or without amino acid supplementation. Without amino acid supplementation, the 50% replacement diet gave slightly better performance during phase 1 (+4% gain, +9% feed efficiency). However, the 100% replacement diets did not perform as well as the control (overall performance reduced by 3 to 13%). Additional refinement (cuticle removal and rendering) may be necessary to make black soldier fly prepupae meal suitable for early weaned pigs (Newton et al., 2005).

Poultry. As a component of a complete diet, black soldier fly larvae meal has been found to support good growth in chicks. Chicks fed a diet containing dried black soldier fly larvae (as a substitute for soymeal) gained weight at a rate 96% (non-significant) of that of chicks fed the control diet containing soymeal, but they only consumed 93% (significant) as much feed (Hale, 1973 cited by Newton et al., 2005), suggesting higher feed conversion efficiency of diet containing the larvae meal.

Ruminants. To the best of our knowledge no studies are available.

2.2.2 Fish

Several experiments have shown that black soldier fly larvae could partially or fully substitute for fishmeal in fish diets. However, additional trials as well as economic analyses are necessary because reduced performance has been observed in some cases, and the type of rearing substrate and the processing method affect the utilization of the larvae by fish.

Channel catfish (Ictalurus punctatus). Chopped soldier fly larvae grown on hen manure fed to channel catfish alone or in combination with commercial diets resulted in similar performance (body weight and total length) as on the control diets (young catfish refused whole larvae but consumed chopped ones). Aroma and texture of channel catfish fed larvae were acceptable to the consumer (Bondari and Sheppard, 1981). A later study was less favourable: replacement of 10% fishmeal with 10% dried soldier fly larvae resulted in slower growth over a 15-week period for sub-adult channel catfish grown in cages. However, the replacement did not reduce growth rate significantly when channel catfish were grown in culture tanks at a slower growth rate. Feeding 100% larvae did not provide sufficient DM or CP intake for good growth for channel catfish grown in tanks. Chopping of the larvae improved weight gain and increased feed consumption in channel catfish, but resulted in lower feed efficiency. Greater larvae waste was observed in the chopped larvae fed tanks than in the whole larvae fed tanks, and chopping was considered to be unnecessary in channel catfish feeding (Bondari and Sheppard, 1987). A comparison between menhaden fishmeal and black soldier fly prepupae meal showed that the latter could be advantageous as a replacement for fishmeal provided it was also supplemented with soybean meal in order to obtain isoproteic diets. It was shown that an inclusion rate higher than 7.5% of black soldier fly prepupae meal was unnecessary (Newton et al., 2005). In yellow catfish, 25% replacement of fishmeal by black soldier fly larva powder produced no significant difference in the growth index and immunity index when compared with those in control group (Zhang et al., 2014b).

Blue tilapia (Oreochromis aureus). Chopped black soldier fly larvae (grown on hen manure) fed to blue tilapia alone or in combination with commercial diets resulted in similar performance (body weight and total length) as the control diets. Aroma and texture of tilapia fed larvae were acceptable to the consumer (Bondari and Sheppard, 1981). In a later experiment, feeding dry black soldier fly larvae as the sole component of the diet did not provide sufficient dry matter or protein intake for good growth for tilapia grown in tanks. Chopping of the larvae however improved weight gain by 140% and feed efficiency by 28% when it was used as the sole component of the diet (Bondari and Sheppard, 1987).

Rainbow trout (Oncorhynchus mykiss). Dried ground black soldier fly prepupae reared on dairy cattle manure enriched with 25 to 50% trout offal could be used to replace up to 50% of fishmeal protein in trout diets for 8 weeks without significantly affecting fish growth or the sensory quality of trout fillets, though a slight (but non-significant) reduction in growth was observed (Sealey et al., 2011). In a 9-week study, replacing 25% of the fishmeal protein in rainbow trout diets with black soldier fly prepupae meal (reared on pig manure) did not affect weight gain and feed conversion ratio (St-Hilaire et al., 2007a).

Atlantic salmon (Salmo salar). A control diet containing 200 g/kg fishmeal (FM) was stepwise replaced by insect meal (black soldier fly larvae) at 25%, 50% or 100% FM replacement. Insect meal containing diets performed equally well as the FM group and increase in feed conversion efficiency was observed. Histology did not show any differences between any of the dietary groups and sensory testing of fillets did not reveal any significant difference (Lock et al., 2014). However, these authors did caution that the method of preparation of insect meal could impact performance.

Turbot (Psetta maxima). Juvenile turbot accepted diets containing 33% defatted black fly soldier larvae meal (as a replacement of fishmeal) without significantly affecting feed intake and feed conversion. However, specific growth rate was lower at all the inclusion rates and higher inclusion rates decreased the acceptance of the diet. This resulted in reduced feed intake and lower growth performance. The presence of chitin might have reduced feed intake and nutrient availability and therefore reduced growth performance and nutrient utilization (Kroeckel et al., 2012).

2.2.3 Crustaceans

Giant river prawn (Macrobrachium rosenbergii). Frass (excrements) from black soldier fly larvae reared on dried distillers grains were used in commercial prawn farms in Ohio (replacing the commercial regular feed). It resulted in similar performance as with the regular prawn feed, with better economic returns. The prawns fed black soldier fly larvae frass were of a lighter colour and no difference in prawns taste was found (Tiu, 2012).

2.2.4 Other species

Alligator (Alligator mississippiensis Daudin*)*. Dried black soldier fly pupae (reared on food waste) fed to juvenile alligators in a 3-month trial were less accepted than a commercial feed and therefore not recommended, even though they were able to promote growth (Bodri and Cole, 2007).

Mountain chicken frogs (Leptodactylus fallax). Black soldier fly larvae have poor nutrient digestibility in Mountain chicken frogs. Digestibilities of almost all nutrients except Na and K could be enhanced through processing (pureeing). After processing or chewing that broke exoskeleton*,* black soldier fly larvae could supply high levels of dietary minerals without a need for additional external Ca. Ca and P digestibilities were approximately two-fold in the mashed worms (about 90% versus 45-50%) and were similar to values measured for supplemented cricket-based diets (Dierenfeld and King, 2008).

3 Housefly maggot meal and housefly pupae meal

The housefly (*Musca domestica* Linnaeus 1758) is the most common fly (Diptera) species. It is a worldwide pest and a major carrier of diseases, as both the larvae (maggots) and the adult flies feed on manure and decaying organic wastes. The ability of housefly maggots to grow on a large range of substrates can make them useful to turn wastes into a valuable biomass rich in protein and fat. Since late 1960s production of housefly maggot biomass in controlled conditions to feed farm animals has been investigated (Calvert et al., 1969; Miller and Shaw, 1969). Particularly, housefly larvae grown on poultry litter have been shown to be used with great benefits as a potential protein source in poultry nutrition (Pretorius, 2011), and since the late 2000s the use of housefly maggots to feed fish and crustaceans in pond farming has been studied extensively. Other Musca species, such as the face fly *M. autumnalis* (De Geer), have been investigated to a lesser extent, (Koo et al., 1980).

The optimal production of maggots requires warm temperatures (> 25°C) and moisture. Under natural conditions, housefly eggs hatch after 8 to 12 h. The larval stage lasts about 5 days and the pupal stage 4 to 5 days. This 10-day cycle can be shortened to 6 days under controlled conditions. Adult female flies lay 500-600 eggs under natural conditions and more than 2000 eggs under controlled ones. The flies lay eggs in moist substrates such as manure and garbage heaps. Maggots feed for 4-5 days and then migrate to pupate in a dry place. The adult fly feeds mainly on decaying organic matter. It needs to liquefy the food by regurgitating droplets of saliva, thereby transmitting pathogens. The flies mate and lay eggs between feeding periods. Large populations of flies can be obtained from relatively small amounts of substrate; for instance, 450 g of fresh manure can feed 1500 maggots (Hardouin and Mahoux, 2003).

Various methods for producing and harvesting maggots have been described in the literature. Early experiments investigated pupae rather than larvae because pupae collection was believed to be easier (Calvert et al., 1969) but the technical issues related to collection of the larvae have since been solved. Poultry manure is the most common substrate cited in the literature for housefly rearing (Akpodiete et al., 1997; Hardouin and Mahoux, 2003), sometimes a fly-attractant like animal offal or rotten fruit (Odesanya et al., 2011) has been ued. Other substrates mentioned in the literature include: pig manure (Viroje et al., 1988; Zhu et al., 2012), cattle blood and wheat bran (Aniebo et al., 2008), cattle blood and gut contents (Dankwa et al., 2002), cattle gut and rumen contents (Ekoue and Hadzi, 2000), fish guts (Ossey et al., 2012) and a mixture of egg content, hatchery waste and wheat bran (Ebenso and Udo, 2003). The main technique consists of filling tanks or crates with manure sprinkled with water regularly to keep the manure wet and attract the flies. A moisture range of 60 to 75% is suitable for larval development. Temperatures should be in the 25-30°C range since maggots are inactive and develop poorly at below 20°C (Miller et al., 1974).

Maggots are harvested by several methods. In the flotation method, the manure is mixed with water and the larvae and pupae float out to be collected with a sieve. In the screening method, the manure is spread in a thin layer on a screen net (3 mm) placed over a basin: the larvae try to escape the sunlight by passing through the screen and fall into the basin (Sogbesan et al., 2006). The collected larvae are washed, killed in tepid or hot water and then dried and milled. More sophisticated collection methods that make the larvae self-collect have been designed (El Boushy et al., 1985).

Housefly larvae are able to break up and dry out large amounts of poultry manure, and this ability makes them a potential biological tool for waste management in poultry farms (El Boushy et al., 1985).

3.1 Chemical constituents of housefly maggot meal

Housefly maggots (also called as: maggot meal, housefly maggots, house fly maggots, magmeal) are a source of protein and lipids. Their contents are high but extremely variable. The CP content varies between 40 and 60% (Table 4). Lipid content is even more variable and ranges between 9 to 26%. Older larvae contain less CP and more lipids (Inaoka et al., 1999; Aniebo et al., 2008; Aniebo and Owen, 2010) (this is not reflected in average values due to the high variability of larvae composition). Sun-drying may in some cases results in lower CP and higher lipids than oven-drying (Aniebo and Owen, 2010). Maggots contain a low (usually lower than 9%) but not negligible amount of crude fibre (CF) (Table 4), but higher values have been reported for acid detergent fibre (ADF). P contents in housefly maggots are of similar order as in black soldier fly larvae but Ca levels are lower by about 15 times (Table 5). Lysine content in housefly maggots, similar to that in black soldier larvae, is also high (from 5. to 8.2 g/ 100 g CP with an average of 6.1 g/100 g CP) (Table 6). The fatty acid profile is presented in Table 7. It is largely influenced by substrate composition with fatty acid composition being one of the first observed changes in the larvae in response to changes in substrate composition. For instance, larvae fed milk powder, sugar and layer manure had a fatty acid profile suitable for broiler growth (Hwangbo et al., 2009). Palmitoleic acid level (17.1%) in housefly maggot (Table 7) is much higher (4 to 15 times) than that in mealworm and house cricket (for the levels see respective sections), while that of linoleic acid (Table 7) is much lower in housefly maggots compared with those in the other two insects.

Table 4. Chemical composition of housefly maggot meal

Crude protein (% in DM), n=29	**Crude fibre (% in DM), n=19**	**Ether extract (% in DM), n=25**	**Ash (% in DM), n=27**	**Gross energy (MJ/kg DM), n=7**
50.4 ± 5.3 (42.3, 60.4)	5.7 ± 2.4 (1.6, 8.6)	18.9 ± 5.6 (9.0, 26.0)	10.1 ± 3.3 (6.2, 17.3)	22.9 ± 1.4 (20.1, 24.4)

DM, dry matter; Values in parentheses are minimum and maximum values; values are mean ± standard deviation

Sources : Adesina et al. (2011); Adewolu et al. (2010); Akpodiete et al. (1997); Aniebo et al. (2008); Aniebo et al. (2010); Atteh et al. (1993); Awoniyi et al. (2003); Bamgbose (1999); Cadag et al. (1981); Fasakin et al. (2003); Göhl (1982); Hwangbo et al. (2009); Ocio et al. (1979); Odesanya et al. (2011); Ogunji et al. (2008); Ogunji et al. (2009); Okah et al. (2012); Pretorius (2011); Sogbesan et al. (2006); Téguia et al. (2002); Zuidhof et al. (2003).

Table 5. Mineral content of housefly maggot meal (all values in g/kg DM except Mn, Cu and Zn which are in mg/kg DM)

Ca, n=10	**P, n=6**	**K, n=7**	**Na, n=8**	**Mg, n=6**	**Fe, n=6**	**Mn, n=7**	**Cu, n=7**	**Zn, n=7**
4.7 ± 1.7 (3.1, 8.0)	16.0 ± 5.5 (9.7, 24.0)	5.7 ± 3.5 (1.0, 12.7)	5.2 ± 2.4 (2.8, 8.6)	3.4 ± 4.0 0.7, 11.5)	1.0 ± 0.44 (0.28, 1.37)	91 ± 114 (40, 349)	27.0 + 6.0 (18.0, 36.0)	119.0 ± 118 (43, 325)

Values are mean ± standard deviation; DM, dry matter; values in parentheses are minimum and maximum values

Sources : Bamgbose (1999); Cadag et al. (1981); Fasakin et al. (2003); Göhl (1982); Hwangbo et al. (2009); Odesanya et al. (2011); Pretorius (2011); Zuidhof et al. (2003).

Table 6. Amino acid composition of housefly maggot meal

Amino acids	g/16 g Nitrogen
Alanine (n=8)	5.8 ±1.0 (4.4, 7.6)
Arginine (n=9)	4.6±0.7 (3.7, 5.8)
Aspartic acid (n=7)	7.5 ± 1.5 (4.5, 8.5)
Cystine (n=4)	0.7 ± 0.2 (0.5, 1.0)
Methionine (n=8)	2.2 ± 0.8 (1.3, 3.7)
Lysine (n=9)	6.1 ± 0.9 (5.0, 8.2)
Isoleucine (n=8)	3.2 ± 0.5 (2.3, 3.7)
Leucine (n=9)	5.4 ± 0.6 (4.5, 6.4)
Phenylalanine (n=8)	4.6 ± 0.8 (3.7, 5.9)
Threonine (n=8)	3.5 ± 07 (2.0, 4.1)
Tryptophan (n=2)	1.5 (1.4, 1.5)
Glutamic acid (n=8)	11.7 ± 1.8 (8.9, 15.3)
Histidine (n=8)	2.4 ± 0.8 (1.0, 3.6)
Proline (n=4)	3.3 ± 0.7 (2.5, 4.7)
Serine (n=8)	3.6 ± 0.5 (2.6, 3.9)
Glycine (n=8)	4.2 ± 0.4 (3.7, 5.1)
Tyrosine (n=7)	4.7 ± 1.4 (2.9, 7.1)
Valine (n=9)	4.0 ± 1.1 (1.3, 4.9)

Values are mean ± standard deviation; values in parentheses are minimum and maximum values

Sources : Akpodiete et al. (1997); Aniebo et al. (2008); Hwangbo et al. (2009); Ocio et al. (1979); Odesanya et al. (2011); Ogunji et al. (2008); Pretorius (2011); Zuidhof et al. (2003).

3.2 Chemical constituents of housefly pupae meal

It is also called as house fly pupae. In general, housefly pupae meal contains higher CP, higher CF and lower lipids than house fly larvae meal. An average CP and CF contents of 71% and 15.7% have been observed (Table 8). Ca and P values of 5.2 and 17.2 g/kg DM are almost similar to those in house fly larvae meal (Table 5). Lysine content in house fly pupae (5.5 g/100 g CP) is slightly lower than that in house fly larvae (Table 6). The same has been the pattern in sulphur-containing amino acids (methionine plus cystine) (Tables 6 and 9). The fatty acid composition of housefly pupae meal and housefly larvae meal also appear to be similar (Tables 7 and 10).

Table 7. Chemical composition of housefly pupae meal

Crude protein (% in DM), n=3	**Crude fibre (% in DM), n=1**	**Ether extract (% in DM), n=3**	**Ash (% in DM), n=3**	**Gross energy (MJ/kg DM)**
70.8 ± 5.3 (65.7, 76.2)	15.7	15.5 ± 1.0 (14.4, 16.1)	7.7 ± 2.1 (5.5, 9.8)	24.3

Values are mean ± standard deviation; DM, dry matter; values in parentheses are minimum and maximum values

Sources : Calvert et al. (1969); Pretorius (2011); St-Hilaire et al. (2007).

Table 9. Amino acid composition of housefly pupae meal

Amino acids	**g/16 g Nitrogen**
Alanine (n=3)	4.2 ± 0.2 (4.1, 4.4)
Arginine (n=3)	4.9 ± 0.9 (4.2, 5.9)
Aspartic acid (n=3)	7.9 ± 1.2 (6.5, 8.7)
Cystine (n=1)	0.4
Methionine (n=3)	2.0 ± 0.6 (1.5, 2.6)
Lysine (n=3)	5.5 ± 0.9 (4.8, 6.5)
Isoleucine (n=3)	3.4 ± 0.2 (3.2, 3.5)
Leucine (n=3)	5.2 ± 0.3 (4.9, 5.4)
Phenylalanine (n=3)	4.2 ± 0.5 (3.7, 4.7)
Threonine (n=3)	3.2 ± 0.2 (3.0, 3.4)
Glutamic acid (n=3)	10.2 ± 2.1 (7.8, 12.0)
Histidine (n=3)	2.0 ± 0.6 (1.5, 2.6)
Proline (n=2)	3.4 (3.1, 3.7)
Serine (n=3)	3.1 ± 0.4 (2.7, 3.4)
Glycine (n=3)	4.1 ± 0.2 (3.9, 4.3)
Tyrosine (n=3)	4.9 ± 0.4 (4.6, 5.3)
Valine (n=3)	4.2 ± 0.7 (3.4, 4.6)

Values in parentheses are minimum and maximum values; values are mean ± standard deviation

Sources : Calvert et al. (1969); Pretorius (2011); St-Hilaire et al. (2007).

Table 10. Fatty acid composition of housefly pupae meal

Fatty acids	% Fatty acid
Lauric acid C12:0 (n=2)	0.4 (0.2, 0.6)
Myristic acid C14:0 (n=3)	2.8 ± 0.3 (2.6, 3.2)
Palmitic acid C16:0 (n=3)	29.6 ± 4.6 (26.4, 34.9)
Palmitoleic acid C16:1 (n=3)	13.3 ± 7.5 (5.6, 20.6)
Stearic acid C18:0 (n=3)	3.2 ± 1.4 (2.2, 4.8)
Oleic acid C18:1 (n=2)	18.7 (18.3, 19.2)
Linoleic acid C18:2 (n=2)	16.4 (14.9, 17.8)
Linolenic acid C18:3	2.1

Values are mean ± standard deviation; values in parentheses are minimum and maximum values

Sources : Calvert et al. (1969); Pretorius (2011); St-Hilaire et al. (2007).

3.3 Nutritional value for different animal species

Most trials have been done with sun-dried (or oven-dried) and ground larvae. There have been some attempts at defatting or hydrolyzing the maggots (Fasakin et al., 2003). Housefly maggots can also be fed live, especially to backyard chickens (Ekoue and Hadzi, 2000; Dankwa et al., 2002) and fish (Ebenso and Udo, 2003; Madu and Ufodike, 2003).

3.3.1 Livestock

Pigs. There is limited information on the use of housefly maggot meal for pig feeding. In Russia, sows and their offspring were fed a diet containing processed housefly maggot meal with no adverse effect on piglet performance, health and organoleptic properties or on the sows' physiology and breeding performance (Bayandina and Inkina, 1980). In Thailand, weaned pigs were fed on soybean based diet supplemented with 10% maggot meal to replace fishmeal and provided isoenergetic and isoproteic diet. This diet had no negative effect on body weight gain or feed conversion efficiency (Viroje et al., 1989). In Nigeria, early weaned pigs were fed 10% of a 3:1 mixture of dried rumen contents and maggot meal in the diet replacing 10 % wheat offal without any adverse effect on performance (Adeniji, 2008).

Rural poultry. Live maggots can be a valuable supplement to the diet of rural chickens. In Ghana, the supplementation of 30-50 g/d/bird of live maggots to scavenging backyard chickens resulted in higher growth rate (until the 5th month) and in higher clutch size, egg weight, number of eggs hatched, and chick weight (Dankwa et al., 2002). A similar preliminary test in Togo was also promising, as the chickens seemed particularly fond of moving larvae (Ekoue and Hadzi, 2000).

Poultry. Poultry farms in subtropical and tropical countries are potential consumers of housefly maggot meal. While initial investigations were carried out in the United States, most of the studies have been or are being done in sub-Saharan Africa (especially Nigeria) and to a lesser extent in Asia. There are limited data on the metabolizable energy (ME) value of housefly maggots (17.9 MJ/kg DM, Zuidhof et al., 2003; 14.2 MJ/kg DM, Pretorius, 2011). This energy value is highly dependent on the fat content and on the amount of "fibre". Total tract amino acid digestibility is high (95%, Zuidhof et al., 2003; 91%, Pretorius, 2011).

Broilers. Maggot meal has been included in broiler diets as a replacement for conventional protein sources, notably fishmeal. Most trials indicate that partial or even total replacement of fishmeal is possible, though the optimal inclusion rate is generally lower than 10% in the diet. Higher rates have resulted in lower intake and performance, perhaps due to the darker colour of the meal which may be less appealing to chickens (Table 11) (Atteh and Ologbenla., 1993; Bamgbose, 1999). Other reason could be imbalanced amino acid profile which generally becomes apparent at high levels of inclusion. Methionine supplementation might enhance performance. In a Nigerian study, meat obtained from broilers fed a maggot-based diet was found to have no distinctive organoleptic qualities and to be acceptable by consumers (Awoniyi, 2007).

Table 11. Intake and performance of broilers fed house fly larvae meal (maggot meal)

Country	Animal	Experiment	Results	Reference
Nigeria	25-day broilers	Maggot meal replacing 0-100% groundnut cake	Could replace 100% groundnut cake (22% diet as fed) without adverse effect on performance. Non significant trend to lower feed intake and weight gain at 75 and 100% substitution.	Adeniji, 2007
Nigeria	120-day broilers	4:1 mixture of dried cassava peels and maggot meal replacing 0-100% maize grain	Cassava peels-maggots mixture could replace 50% maize (29% diet as fed) in order to save cost	Adesina et al., 2011
Nigeria	0-56 days broilers	Maggot meal replacing 75% fish meal protein	No adverse effect on performance, and higher economic returns	Akpodiete and Inoni, 2000
Nigeria	0-5 weeks broilers	Maggot meal replacing 0-100% fish meal	Could replace up to 33% fish meal (9% diet as fed) without adverse effect on intake and weight gain. At higher rates, lower intake could be associated to the darker colour of the maggot diets.	Atteh and Ologbenla., 1993
Nigeria	3-week broilers	Maggot meal replacing 0-100% fish meal protein	Could replace up to 25% fish meal protein (1.17% diet as fed) for profitable results	Awoniyi et al., 2003
Nigeria	0-8 weeks broilers	Maggot meal replacing 0-100% meat and bone meal	Could replace up to 100% meat and bone meal (8% diet as fed) if the diet is supplemented with methionine.	Bamgbose, 1999
Philippines	21-day broilers	Maggot meal compared to fish meal, meat and bone meal and soymeal at 10% inclusion (DM basis)	Could be included at up to 10% in the diet with no adverse effect on intake, body weight, feed conversion and palatability	Cadag et al., 1981
United States	0-2 weeks broilers	Pupae meal replacing 100% soybean meal	Could replace soymeal with no effect on gain, intake and feed efficiency	Calvert et al., 1969
South Korea	0-3 and 3-5 weeks broilers	0-20% maggot meal in a balanced diet	Maggot supplementation caused increased live weight gain but had no effect on the feed conversion ratio. The 10-15% maggots containing diet gave the best weight gain for the 4-5 weeks broilers and increased dressing percentage, breast muscle, thigh muscle, muscle lysine and tryptophan levels.	Hwangbo et al., 2009
Japan	0-24 day broilers	7% maggot meal in a balanced diet replacing 7% fish meal (weight basis)	Identical growth performance, feed conversion ratio and meat composition, higher dressing percentage in maggot-fed broilers	Inaoka et al., 1999
Nigeria	35-day broilers	Maggot meal replacing 0-50% fish meal	Could replace 50% fish meal (2% diet as fed) with higher performance and economic returns	Okah and Onwujiariri, 2012
South Africa	0-35 day broilers	10-50% maggot meal in the diet	The 25% maggot meal diet yielded better live weights, feed intake and daily gain when compared to the 25% fish meal diet in the growth phases. Chicks that received either the 10% house fly larvae meal or 10% fish meal supplementation produced significantly heavier carcasses and breast muscle portions than the chicks that received the commercial maize:soymeal. No treatment differences were found regarding breast and thigh muscle colour or pH.	Pretorius, 2011
China	Yellow dwarf 8-63 days broilers	4.4% maggot meal (DM basis) added to basal diet	Supplementation with maggot meal enhanced feed intake and average daily gain at 8-21 days with no negative effect on the slaughter performance and meat quality. Performance differences were non-significant a later stages	Ren et al., 2011
Cameroon	0-42 day broilers	Maggot meal replacing 0-15% fish meal (0-6.75% in diet) in starter diets and 0-100% (0-	The replacement of fish meal with maggot meal in starter and grower finisher diets resulted in higher weight gain and comparable carcass yield.	Téguia et al.,

		20% diet) in finisher diets		2002
United States	0-7 weeks broilers	28% pupae meal in the diet ,replacing other protein sources (soymeal 30%, fish meal 3% and meat and bone meal 5%)	No difference in growth rate, carcass quality and taste but lower final weight and feed intake for pupae-fed broilers	Teotia and Miller, 1973
United States	0-4 weeks broilers	8% pupae meal in the diet, replacing fish meal 3% and meat and bone meal 5%	No difference in growth rate	Teotia and Miller, 1973

Laying hens. In a 7-month layer feeding trial, maggot meal replaced meat and bone meal and the results showed that maggot meal increased egg yield and hatchability (Ernst et al., 1984). In 50-week laying hens, maggot meal could replace 50% of fishmeal protein (5% in diet) without adverse effects on egg production and shell strength. However, 100% replacement was deleterious to hen-egg production (Agunbiade et al., 2007).

Ruminants. To the best of our knowledge no information is available on ruminants.

3.3.2 Fish

The use of housefly maggots as supplements in the diets of tilapia and catfish species (*Clarias gariepinus* and *Heterobranchus longifilis*) has been reported in Nigeria (Madu and Ufodike, 2003).

African catfish Clarias gariepinus, Heterobranchus longifilis and hybrids. There have been a number of experiments in Nigeria on the use of housefly maggots in the diets of African catfish, mostly *Clarias gariepinus*. The results are generally positive though the inclusion of maggot meal should be limited to 25-30% because performance tends to decrease when higher inclusion rates are used (Table 12).

Nile tilapia (Oreochromis niloticus). Nile tilapia fed a 4:1 mixture of wheat bran and live maggots had a better growth performance, specific growth rate, feed conversion ratio and survival than fish fed a diet containing only wheat bran (Ebenso and Udo, 2003). In another experiment, maggot meal was included at 15 to 68% in the diet, replacing fishmeal. The best performance and survival was obtained at a level of 25% maggot meal (replacing 34% fishmeal) in the diet. Maggot meal was beneficial to fish growth and performance and no adverse effects on the haematology and homeostasis were observed. However, to enhance the fatty acid profile in fish, adequate sources of n-6 and n-3 fatty acids should be included in the diet (Ogunji et al., 2007; Ogunji et al., 2008a,b).

Table 12. Intake and performance of fish and crustaceans fed housefly larvae meal (maggot meal)

Country	Animal	Experiment	Results	Reference
Nigeria	*Clarias gariepinus* fingerlings	4:3:2 mixture of feather meal, chicken offal meal and maggot meal replacing 0-100% fish meal	Could replace 50% fish meal (30% diet as fed) without adverse effect on weight gain, specific growth rate, feed conversion ratio, and protein efficiency ratio. Lower performance at 75 and 100% substitution.	Adewolu et al., 2010
Nigeria	*Clarias gariepinus* fingerlings	Maggot meal (produced on cattle blood and wheat bran substrate) replacing 0-100% fish meal	Could replace 100% fish meal (25% diet as fed) without adverse effect on growth performance and nutrient utilization.	Aniebo et al., 2009
Nigeria	*Clarias gariepinus* fingerlings	Full-fat sun-dried and oven-dried maggot meal replacing fish meal	Fish fed 34-35% full-fat maggot meal had lower growth performance and survival than fish fed 25% fish meal.	Fasakin et al., 2003
Nigeria	*Clarias gariepinus* fingerlings	Defatted, sun-dried and oven-dried maggot meal replacing fish meal	Fish fed 27% defatted oven-dried maggot meal (27% in the diet) had similar growth performance and survival than fish fed 25% fish meal	Fasakin et al., 2003
Nigeria	*Clarias gariepinus* fingerlings	Maggot meal included from 12.5% to 100% in the diet	Maggot meal was detrimental to growth performance at all levels (particularly at 100%) though nutrient utilization was less affected.	Idowu et al., 2003
Nigeria	*Clarias anguillaris* fingerlings	Live maggots (100% if the diet) or 1:1 mixture of live maggots and commercial diet at 40% protein	Best growth performance and economic gain were obtained with the live maggots/commercial diet	Madu and Ufodike, 2003
Cote d'Ivoire	*Heterobranchus longifilis*	Comparison between soymeal, cattle brain meal and maggot meal included at > 80%	Maggot meal gave better performance than soymeal and lower performance than cattle brains. However, maggot meal was much less expensive than the latter feed	Ossey et al., 2012
Nigeria	*Heterobranchus longifilis* (f) x*Clarias gariepinus*(m)	Maggot meal replacing 0-100% fish meal (0-30% in diet)	Best growth performance was obtained at 25% replacement (7.5% inclusion in diet). 100% replacement (30% inclusion in diet) is economically viable	Sogbesan et al., 2006

3.3.3 Crustaceans

Whiteleg shrimp (Litopenaeus vannamei). In juvenile whiteleg shrimps fed diets containing housefly maggot meal, rate of weight gain, feed conversion ratio, protein efficiency ratio and productive protein value were maintained with diets in which maggot meal replaced up to 60% of fishmeal protein. Specific growth rate tended to decrease with maggot meal inclusion. At substitution levels lower than 60%, there were neither significant effects on digestive enzymes and transaminases activities nor serious injury to hepatopancreas histological structure, but higher levels of inclusion were not recommended (Cao et al., 2012a,b).

Chinese white shrimp (Fenneropenaeus chinensis) and Japanese blue crab (Portunus trituberculatus). In juvenile Chinese white shrimps, the addition of housefly maggot meal had positive effects on body length, body weight, specific growth rate and survival, and an inclusion rate of 38% and higher resulted in higher growth. There were significantly lower contents of the essential fatty acids and higher contents of polyunsaturated fatty acids in the muscles of the shrimp fed maggot meal (Zheng Wei et al., 2010a). In a polyculture of Chinese white shrimps and Japanese blue crab fed a diet containg 30-50% housefly maggot meal, the yields of the shrimp and crab were 80% and 20% higher than those on control diets. Survival rates for maggot-fed shrimps and crabs were 11% and 3% higher than those in the control pond. Shrimps and crabs fed the maggot meal diet had significantly higher body weight, especially in the mid- and late-culture period (Zheng et al., 2010b).

3.3.4 Other species

Rats. Maggot meal could be included at 5% in the diets of young rats as a partial replacement for fishmeal in isoproteic and isoenergetic diets for optimal weight performance and nutrient utilization (Bouafou et al., 2011a). However, inclusion of 10% maggot meal resulted in histological changes (fibrosis) in the liver and the kidneys (Bouafou et al., 2011b).

3.4 Potential constraints

The housefly is a known carrier of pathogens and the inclusion of maggot meal in livestock diets raises concerns about potential transmission of diseases. Particularly, there is a risk when bacteria or fungi are present in the maggot-rearing substrate (usually manures of different animal species), which can carry over to the finished maggot meal, especially when the keeping quality of the maggot meal is uncertain. However, contaminations due to feeding of maggot meal to poultry or fish have not been reported.

In Nigeria, 9 month-old stored samples of dried, milled housefly larvae were found to be prone to deterioration by fungi and bacteria when the moisture content was too high (23%). It was recommended to dry the meal to 4-5% moisture to minimize bacterial activity. After processing, moisture absorption could be prevented by waterproof bagging (with cellophane or nylon) and heat-sealing (Awoniyi et al., 2004b). Adequate heating should take place during the drying process to assure destruction of any pathogenic organism present in the larvae (Rocas, 1983).

One experiment reported an increase in liver and gizzard mass in broilers when the level of maggot meal in the diet increased from 1% to 2% (50 to 100% substitution of fishmeal; weight basis), suggesting potential toxic effects (Téguia et al., 2002), but a later experiment reported that housefly larvae meal included at up to 50% to replace fishmeal in broiler soybean-maize based diets did not induce gizzard erosion or show toxicity in the gastro intestinal tract. Also immune system was not affected (Pretorius, 2011). An experiment on rats has reported histological damages on liver and kidneys when maggot meal was included at 10% in the maize flour/fishmeal-based diet (Bouafou et al., 2011b).

4 Mealworm (*Tenebrio molitor*)

Mealworms are the larvae of two species of darkling beetles of the Tenebrionidae family, the yellow mealworm beetle (*Tenebrio molitor* Linnaeus, 1758) and the smaller and less common dark or mini mealworm beetle (*Tenebrio obscurus* Fabricius, 1792). Mealworm beetles are indigenous to Europe and now distributed worldwide. *Tenebrio molitor* is a pest of grain, flour and food stores, but often not of much importance since their populations are quite small (Ramos-Elorduy et al., 2002). Mealworms are easy to breed and feed and have a valuable protein profile. For these reasons, they are produced industrially as feed for pets and zoo animals, including birds, reptiles, small mammals, amphibians and fish. They are usually fed live, but are also sold canned, dried, or in powder form (Aguilar-Miranda et al., 2002; Hardouin and Mahoux, 2003; Veldkamp et al., 2012).

The life cycle of *Tenebrio molitor* is of variable length, from 280 to 630 days. Larvae hatch after 10-12 days (at 18-20°C) and become mature after a variable number of stages (8 to 20), typically after 3-4 months (at *ambient* temperature), but the larva stage can last up to 18 months. The mature larva is of a light yellow-brown colour, is 20 to 32 mm long and weighs 130 to 160 mg. Commercial mealworm producers sometimes include a juvenile hormone into the feed to prevent the larvae from molting into adults, resulting in "giant" mealworms that can achieve a length of 2 cm or greater and weigh more than 300 mg (Finke, 2002). The pupal stage lasts 7-9 days at 25°C and up to 20 days at lower temperatures. The adult *Tenebrio molitor* lives for two to three months. The life cycle of *Tenebrio obscurus* is shorter, particularly in the larval stage (Hill, 2002; Hardouin and Mahoux, 2003).

Mealworms are omnivorous and can eat all kinds of plant materials as well as animal products such as meat and feathers (Ramos-Elorduy et al., 2002). They are typically fed on cereal bran or flour (wheat, oats, maize) supplemented with protein sources such as soybean flour, skimmed milk powder or yeast. Fresh fruits and vegetables (carrots, potatoes, lettuce) are also included which provide moisture (Aguilar-Miranda et al., 2002; Hardouin and Mahoux, 2003). The diet should be balanced to contain about 20% protein on dry matter basis (Ramos-Elorduy et al., 2002).

Mealworms are able to utilize small amounts of water contained in dry feeds but the productivity of water-deprived mealworms is low (one generation per year). It is preferable to provide them with a source of water for better productivity (up to 6 generations per year) and in order to prevent cannibalism. Relative humidity is linked positively with fertility and adult activity. It is necessary to monitor fresh feeds as they may turn mouldy (Hardouin and Mahoux, 2003).

Mealworms have the ability to recycle plant waste materials of low quality into high-quality feed rich in energy, protein and fat in a relatively short time. Mealworms have been shown to be able to detoxify zearalenone by partly metabolizing it to alpha-zearalenol. There was no risk of zearalenone accumulating in mealworm larvae to such an extent that they could affect animals which ate them (Hornung, 1991).

4.1 Chemical constituents

Chemical constituents of mealworms (*Tenebrio molitor*) are discussed in this section. These are also called as mealworm, dried mealworms or mealworm meal. They contain high amounts of CP (47-60%) and fat (31-43%) (Table 13). Fresh larvae contain about 60% water. They are relatively low in ash (< 5% DM) and like other insects they have a low Ca content and a very low Ca:P ratio (Table 14). The exclusive feeding of mealworms causes Ca deficiency and symptomatic metabolic bone disease (Klasing et al., 2000). It must be noted that the composition is highly variable and influenced by the diet. Notably, the Ca content can be manipulated using Ca-fortified diets. The essential amino acid composition of the meal is good (Table 15). Fatty acid composition of mealworm is closer to that of housefly maggot meal and house cricket (see subsequent sections). Two fatty acids differ substantially: lauric acid is much lower and linoleic acid much higher in mealworm than in black soldier fly larvae (Table 16)

Table 13. Chemical composition of mealworm

Crude protein (% in DM), n=9	**NDF (% in DM), n=4**	**ADF (% in DM), n=2**	**Ether extract (% in DM), n=8**	**Ash (% in DM), n=10**	**Gross energy (MJ/kg DM), n=4**
52.8 ± 4.2 (47.2, 60.3)	12.0 ± 3.5 (7.4, 15.0)	6.5 (6.4, 6.6)	36.1 ± 4.1 (31.1, 43.1)	3.1 ± 0.9 (1.0, 4.5)	26.8 ± 0.4 (26.4, 27.3)

Values are mean ± standard deviation; DM, dry matter; Values in parentheses are minimum and maximum values; DM of the meal as fed (n=10) was 42.3 ± 6.3 (37.1, 57.6); NDF neutral detergent fibre; ADF acid detergent fibre; NDF/ADF values are averages from Van Soest measurements obtained using different methods (with or without amylase and including or not including residual ash)

Sources : Barker et al., 1998; CIRAD, 1991; Finke, 2002; Jones et al., 1972; Klasing et al., 2000; Martin et al., 1976.

Table 14. Mineral content of mealworm (all values in g/kg DM except Fe, Mn, Zn and Cu, which are in mg/kg DM)

Ca, n=10	**P, n=8**	**K, n=2**	**Na, n=1**	**Mg, n=3**	**Fe, n=5**	**Mn, n=4**	**Zn, n=4**	**Cu, n=4**
2.7 ± 1.9 (0.3, 6.2)	7.8 ± 3.7 (4.4, 14.2)	8.9 (8.5, 9.3)	0.9	2.3 ± 0.4 (2.0, 2.8)	57.0 ± 32.0 (26.0, 110.0)	9.0 ± 4.0 (6.0, 14.0)	116.0 ± 24.0 (83.0, 136.0)	16.0 ± 1.0 (15.0, 18.0)

Values are mean ± standard deviation; DM, dry matter; values in parentheses are minimum and maximum values

Sources : Barker et al., 1998; CIRAD, 1991; Finke, 2002; Jones et al., 1972; Klasing et al., 2000; Martin et al., 1976.

Table 15. Amino acid composition of mealworm

Amino acids	**g/16 g Nitrogen**
Alanine (n=3)	7.3 ± 1.0 (6.2, 8.2)
Arginine (n=3)	4.8 ± 1.0 (3.8, 5.6)
Aspartic acid (n=3)	7.5 ± 1.7 (5.6, 8.8)
Cystine (n=3)	0.8 ± 0.0 (0.8, 0.9)
Methionine (n=3)	1.5 ± 0.4 (1.3, 2.0)
Lysine (n=3)	5.4 ± 0.8 (4.6, 6.1)
Isoleucine (n=3)	4.6 ± 0.5 (4.1, 5.0)
Leucine (n=3)	8.6 ± 1.8 (7.4, 10.6)
Phenylalanine (n=3)	4.0 ± 0.4 (3.5, 4.3)
Threonine (n=3)	4.0 ± 0.5 (3.5, 4.4)
Tryptophan (n=3)	0.6 ± 0.5 (0.0, 0.9)
Glutamic acid (n=3)	11.3 ± 1.1 (10.2, 12.4)
Histidine (n=3)	3.4 ± 0.2 (3.2, 3.6)
Proline (n=3)	6.8 ± 0.2 (6.6, 7.0)
Serine (n=3)	7.0 ± 3.5 (4.9, 11.1)
Glycine (n=3)	4.9 ± 0.9 (3.9, 5.6)
Tyrosine (n=3)	7.4 ± 0.3 (7.1, 7.8)
Valine (n=3)	6.0 ± 0.6 (5.5, 6.6)

Values are mean ± standard deviation; values in parentheses are minimum and maximum values

Sources : Finke, 2002; Jones et al., 1972.

Table 16. Fatty acid composition of mealworm

Fatty acids	% Fatty acid
Lauric acid C12:0	0.5 ± 0.5 (0.0, 1.0)
Myristic acid C14:0	4.0 ± 2.1 (2.3, 6.4)
Palmitic acid C16:0	21.1 ± 6.7 (16.1, 28.7)
Palmitoleic acid C16:1	4.0 ± 1.8 (2.8, 6.1)
Stearic acid C18:0	2.7 ± 0.4 (2.3, 3.1)
Oleic acid C18:1	37.7 ± 8.7 (27.7, 43.3)
Linoleic acid C18:2	27.4 ± 4.0 (23.1, 31.0)
Linolenic acid C18:3	1.3 (1.1, 1.4)

n=3 for all the above values except for linolenic acid C18:3 (n=2); values in parentheses are minimum and maximum values

Sources : Finke, 2002; Jones et al., 1972.

4.2 Nutritional value for different animal species

Mealworms are typically fed live but canned and dried larvae are commercially available. In feeding experiments, larvae have been dried at 50°C for 24 h (Klasing et al., 2000) or 3 days (Ramos-Elorduy et al., 2002), 100°C for 200 min (Wang et al., 1996), in the sun for 2 days (Ng et al., 2001) or boiled in water for 3 min and then oven-dried at 60-100°C (Aguilar-Miranda et al., 2002).

4.2.1 Livestock

Poultry. Mealworms are a potential alternative source in poultry diets, in particular for replacing soymeal or fishmeal. The protein quality is similar to that of soymeal, but the methionine content is limiting for poultry (Ramos-Elorduy et al., 2002). The low Ca content is also an issue in poultry diets. The Ca content and the Ca: P ratio of mealworms could be increased by feeding them a Ca-fortified diet for 1-2 days. The addition of 8% $CaCO_3$ was found to be suitable. The Ca supplied by Ca-fortified mealworms was highly available for supporting bone mineralization in growing chicks, although it was slightly less available than the Ca from oyster shells (Klasing et al., 2000). Another experiment also reported that short-term feeding of mealworms with a Ca-fortified commercial diet for 72 h resulted in acceptable Ca contents in the next 24 h (Anderson, 2000).

Broilers. Dried mealworms included up to 10% (on DM basis) in a broiler starter diet based on sorghum and soybean meal could be used without negative effects on feed consumption, weight gain and feed efficiency. There was no observed rejection of feed due to texture, palatability or inclusion level (Ramos-Elorduy et al., 2002).). In another study (Schiavone et al., 2014) , 25% mealworm, as a substitution of the basal diet, was found to be suitable.

Laying hens. There is limited information on the use of mealworms in the diets of laying hens. Larvae from *T. molitor* and *T. mauritanicus* were found to be suitable for layers (Giannone, 2003). Dried ground mealworms could replace fishmeal in the diets of laying hens and resulted in 2.4% higher egg-laying ratio than that obtained with good quality feed (Wang et al*.,* 1996).

Pigs and ruminants. To the best of our knowledge no information is available.

4.2.2 Fish

African catfish (Clarias gariepinus). Fresh and dried mealworms have been found to be an acceptable alternate protein source for the African catfish. Replacing 40% of fishmeal with mealworm (dried and ground) resulted in growth performance and feed utilization efficiency similar to that obtained with the control diet (both control and test diets being isoproteic). Catfish fed isoprteic diets with up to 80% replacement of fishmeal with mealworm meal still displayed good growth and feed utilization efficiency. Catfish fed solely on live mealworms had a slight depression in growth performance but fish fed live mealworms in the morning and commercial catfish pellets in the afternoon grew as good as or better than fish fed the commercial diet. Live and dried mealworms were found to be highly palatable. Catfish fed mealworm-based diets had significantly higher lipids in their carcass (Ng et al., 2001).

Gilthead sea bream (Sparus aurata). A study with gilthead sea bream juveniles fed diets containing mealworm at replacement levels of 25% and 50% of fishmeal protein showed that up to 25% inclusion of the insect meal in diet did not lead to adverse effects on weight gain and final weight, while 50% level induced growth reduction and less favourable outcomes for specific growth rate, feed conversion efficiency and protein efficiency ratio. The whole body proximate composition analysis did not show any differences between treatments. These results showed that the substitution of fishmeal protein in diets for gilthead sea bream juveniles is feasible up to 25% without adverse effects on growth performance and whole body proximate composition (Piccolo et al., 2014).

Rainbow trout (Oncorhynchus mykiss). Mealworm added in a diet (containing 45% CP) at levels of 25% and 50% by weight (as a replacement of fishmeal) showed that mealworm can be used at an inclusion level of up to 50% without a growth performance reduction, leading to a saving of fishmeal (Gasco et al., 2014a).

European sea bass (Dicentrarchus labrax). A study showed that up to 25% inclusion of mealworm in the diet (as a replacement of fishmeal; all diets being isoproteic) did not lead to adverse effects on weight gain, while at 50% level of the mealworm induced reduction in growth, specific growth rate and feed consumption ratio. Protein efficiency ratio, feed consumption and body composition were not affected. On the other hand, mealworm inclusion influenced the fatty acid composition of body lipids (Gasco et al., 2014b).

5 **Locust meal, locusts, grasshoppers and crickets**

The common names are: Locust meal, locusts, desert locust, migratory locust, red locust, grasshoppers, grasshopper meal, katydids, crickets, cricket meal, house cricket, field cricket, Mormon cricket, Orthoptera, Acridids, Acrididae, Gryllidae, Tettigoniidae.

Locusts, grasshoppers (mostly Acrididae and Pyrgomorphidae), crickets (Gryllidae) and katydids (Tettigoniidae) are insects of the order Orthoptera. They are generally edible and more than 80 species of locusts, grasshoppers and crickets are consumed worldwide for human food in Africa, South America and Asia. They may be part of the usual diets or delicacies sold by street vendors. They are eaten at home or in restaurants, both in rural and urban areas (DeFoliart, 1989; Ramos-Elorduy, 1997; van Huis et al., 2013).

Locusts are a group of grasshopper species that become gregarious and migratory when their populations are dense enough. During the swarming phase, locusts destroy or severely damage crops. They are a major pest of historical importance, notably in Africa (North, West, Sahel and Madagascar), Australia and the Middle-East. A locust swarm can represent a considerable amount of biomass. A single swarm can contain up to 10 billion insects and weigh approximately 30,000 tonnes (DeFoliart, 1989; Ramos-Elorduy, 1997; van Huis et al., 2013). The swarming behaviour makes locusts relatively easy to harvest for food. In Africa, the desert locust (*Schistocerca gregaria*), the migratory locust (*Locusta migratoria*), the red locust (*Nomadacris septemfasciata*) and the brown locust (*Locustana pardalina*) are commonly eaten (van Huis et al., 2013). In Japan, China and Korea, rice field grasshoppers (including *Oxya yezoensis, O. velox, O. sinuosa*, and *Acrida lata*) are harvested for food (van Huis et al., 2013). In Mexico, chapulines, which are grasshoppers of the *Sphenarium* genus, and notably *Sphenarium purpurascens*, a pest of alfalfa, are popular edible insects (Cohen et al., 2009). The grasshopper *Ruspolia differens*, which is actually a katydid, is a common food source in many parts of eastern and southern Africa (van Huis et al., 2013). Crickets are a common food in South East Asia, particulary in Thailand. The house cricket *Acheta domestica*, *Gryllus bimaculatus*, *Teleogryllus occipitalis*, *Teleogryllus mitratus*, the short-tail cricket *Brachytrupes portentosus* and *Tarbinskiellus portentosus* are edible cricket species (van Huis et al., 2013).

Grasshoppers, locusts and crickets are usually collected in the wild, preferably at night (using artificial light) or in the morning when the temperature is cooler and the insects are less active and easier to catch. Commercial farming of locusts, grasshopper and crickets for the food and feed market is developing in South East Asia. In 2012, there were about 20,000 cricket farmers in Thailand, raising the species *Acheta domestica* and Gryllus *bimaculatus*. Orthoptera, and particularly locusts, are commonly raised to feed pets and zoo animals (van Huis et al., 2013).

In India, the mass-rearing of grasshopper species *O. fuscovittata*, *O. hyla* and *Spathosternum prasiniferum* has been studied experimentally. The use of jars with a volume of 2500 cm^3 and a density of 10,000 insects per m^3 for *Oxya fuscovittata* and 7100 insects per m^3 for *Spathosternum prasiniferum* resulted in mortality rates of 12 and 15% respectively. The smaller size of *S. prasiniferum* meant that more could be kept per unit area compared with *Oxya fuscovittata* (Das et al., 2009). When comparing *O. hyla* and *S. prasiniferum*, *O. hyla* showed higher fecundity, fertility and body weight and lower nymphal mortality. *Brachiaria mutica* was found to be more suitable than *Dactyloctenium aegyptium* and *Cynodon dactylon* for annual biomass production of both acridids (Das et al., 2012a, b). *Sorghum halepense* has also been proposed as a potential forage plant for *O. fuscovittata* (Ganguly et al., 2010). The house cricket *A. domestica* is easy to farm and can produce from 6 to 7 generations per year. It is omnivorous and can eat a large range of organic materials. Production is feasible at temperatures higher than 20°C and the ideal temperature is 28-30°C. Approximately 2000 insects can be bred in 1 m^2. Cricket population is self-regulated by cannibalism (Hardouin and Mahoux, 2003).

The harvesting of locusts and other pest grasshoppers for food and feed is a means to biological control them, and the harvesting may help to reduce the application of chemical pesticides and thereby environmental pollution (Khusro et al., 2012). For instance, the outbreak of patanga locust (*Patanga succincta*) in maize in Thailand in late 1970s led to a campaign to promote the eating of this locust, which is now farmed for food purposes (van Huis et al., 2013). In Mexico, hand-picking of chapulines grasshoppers infesting alfalfa fields decreased environmental damage while generating an extra source of nutrition and income from the consumption and sale of grasshoppers (Cerritos and Cano-Santana, 2008).

The presence of livestock can also help to control locust populations. In China, free-range chickens at a stocking rate of 3.3 head/ha could control the infestation of pastures by locust species *Oedaleus infernalis, Oedaleus asiaticus, Haplotropis brunneriana, Bryodema tuberculata* and *Locusta migratoria* (Li LianShu et al., 2005). In Australia, chickens have been reported to control populations of wingless grasshopper (*Phaulacridium vinatum*), a pest to viticulture, agricultural crops, pastures and trees (Khusro et al., 2012).

In the United States of America, several studies have shown that cattle grazing practices, especially rotational grazing, could reduce outbreaks of pest grasshoppers such as *Ageneotettix deorum, Aulocara elliotti, Melanoplus* sanguinipes*, Melanoplus packardii* and *Camnula pellucida*, by reducing food availability and by altering microclimate and potential oviposition sites (Onsager, 2000; O'Neill et al., 2003).

5.1 Chemical constituents

Locusts and other Orthoptera species are generally rich in CP (50-65%), though some lower values (<30%) have also been reported. The DM is 23-35%. The fat content is quite variable and ranges from relatively low values (<5%) to high ones (>20%). Ca content is rather poor, as in other insect species (Table 17). The “fibre” content may be significant and increases with age: adult crickets contain up to 22% neutral detergent fibre (NDF) *vs* 12% for the nymphs (Finke, 2002).

Table 17. Chemical composition of locust or grasshopper meal

Crude protein (% in DM), n=9	**Crude fibre, n=7**	**Ether extract (% in DM), n=9**	**Ash (% in DM), n=8**	**Gross energy (MJ/kg DM), n=4**
57.3 ± 11.8 (29.2, 65.9)	8.5 ± 4.1 (2.4, 14.0)	8.5 ± 3.1 (4.2, 14.1)	6.6 ± 2.5 (4.3, 10.0)	21.8 ± 2.0 (19.5, 23.7)

Values are mean ± standard deviation; DM, dry matter; values in parentheses are minimum and maximum values

Sources: Adeyemo et al., 2008; Alegbeleye et al., 2012; Anand et al., 2008; Hemsted, 1947; Ojewola et al., 2005; Walker, 1975.

Ca and P contents (1.3 and 1.1 mg/kg DM respectively) are much lower compared to other insects (black soldier fly meal, maggot meal and housefly meals) while Ca:P ratio is higher which is mainly due to lower P level compared with other insects.

Essential amino acid composition is reasonably good. Level of lysine is lower than other insects such as meals of black soldier fly, maggot and housefly while that of cystine plus methionine is higher (Table 18).

Table18. Amino acid composition of locust or grasshopper meal

Amino acids	**g/16 g Nitrogen**
Alanine (n=2)	4.6 (4.1, 5.1)
Arginine (n=2)	5.6 (3.7, 7.4)
Aspartic acid (n=1)	9.4
Cystine (n=2)	1.1 (0.5, 1.7)
Methionine (n=2)	2.3 (2.3, 2.3)
Lysine (n=2)	4.7 (3.4, 5.9)
Isoleucine (n=2)	4 (3.9, 4.1)
Leucine (n=2)	5.8 (5.6, 5.9)
Phenylalanine (n=2)	3.4 (2.3, 4.5)
Threonine (n=2)	3.5 (2.9, 4.0)
Tryptophan (n=1)	0.8
Glutamic acid (n=1)	15.4
Histidine (n=2)	3.0 (1.9, 4.2)
Proline (n=2)	2.9 (2.1, 3.8)
Serine (n=1)	5.0
Glycine (n=2)	4.8 (4.7, 4.8)
Tyrosine (n=2)	3.3 (3.1, 3.6)
Valine (n=2)	4.0 (3.8, 4.3)

Sources : Alegbeleye et al., 2012; Balogun, 2011.

The CP content of house cricket (*A. domesticus*) is also very high (55 to 67%) (Table 19). Both Ca and P contents in house cricket are higher than in locust or grasshopper meal (Tables 20). Both lysine, and methionine plus cystine contents in house cricket are lower than in locust meal (Tables 18 and 21). The palmitoleic acid level in house cricket is approximately 15-fold lower than that in housefly maggot and 4-fold lower than in mealworm. On the other hand, the level of linoleic acid (Table 22) is higher in house cricket.

Table 19. Chemical composition of house cricket

Crude protein (% in DM), n=4	**Neutral detergent fibre, n=4**	**Acid detergent fibre (% in DM), n=2**	**Ether extract (% in DM), n=4**	**Ash (% in DM), n=4**
63.3 ± 5.7 (55.0, 67.2)	18.3 ± 2.9 (15.7, 22.1	10.0 (9.6, 10.4)	17.3 ± 6.3 (9.8, 22.4)	5.6 ± 2.4 (3.6, 9.1)

DM, dry matter; DM of house cricket (fresh) as fed was 28.4 ± 4.5 (n=4) (22.9, 33.2); values are mean ± standard Division; values in parentheses are minimum and maximum values; NDF/ADF values are averages from Van Soest measurements obtained using different methods (with or without amylase and including or not including residual ash)

Sources: Barker et al., 1998; Finke, 2002.

Table 20. Mineral content of house cricket (all values in g/kg DM except Cu, Mn, Fe and Zn which are in mg/kg DM)

Ca, n=4	**P, n=2**	**Mg, n=2**	**Cu, n=4**	**Mn, n=4**	**Fe, n=4**	**Zn, n=4**
10.1 ± 5.3 (2.1, 13.2)	7.9 (7.8, 7.9)	1.2 (0.8, 1.6)	15.0 ± 7.0 (9.0, 22.0)	40.0 ± 10.0 (30, 53)	116.0 ± 58.0 (63.0, 197.0)	215.0 ± 60.0 (159.0, 297.0)

Values are mean ± standard Division; DM, dry matter; values in parentheses are minimum and maximum values

Sources: Barker et al., 1998; Finke, 2002.

Table 21. Amino acid composition of house cricket

Amino acids	g/16 g Nitrogen
Alanine	8.8 (8.8, 8.9)
Arginine	6.1 (6.1, 6.1)
Aspartic acid	7.7 (7.1, 8.4)
Cystine	0.8 (0.8, 0.8)
Methionine	1.4 (1.3, 1.5)
Lysine	5.4 (5.4, 5.4)
Isoleucine	4.4 (4.3, 4.6)
Leucine	9.8 (9.5, 10.0)
Phenylalanine	3.0 (2.8, 3.2)
Threonine	3.6 (3.6, 3.6)
Tryptophan	0.6 (0.5, 0.6)
Glutamic acid	10.4 (10.4, 10.5)
Histidine	2.3 (2.2, 2.3)
Proline	5.6 (5.5, 5.6)
Serine	4.6 (4.2, 5.0)
Glycine	5.2 (5.1, 5.3)
Tyrosine	5.2 (4.9, 5.5)
Valine	5.1 (4.9, 5.2)

Values in parentheses are minimum and maximum values; n=2 for all above values

Source: Finke (2002).

Table 22. Fatty acid composition of house cricket

Fatty acids	% Fatty acid
Lauric acid C12:0	Not detected
Myristic acid C14:0	0.7 (0.6, 0.7)
Palmitic acid C16:0	23.4 (21.9, 24.9)
Palmitoleic acid C16:1	1.3 (1.1, 1.4)
Stearic acid C18:0	9.8 (9.3, 10.4)
Oleic acid C18:1	23.8 (23.0, 24.6)
Linoleic acid C18:2	38.0 (36.5, 39.5)
Linolenic acid C18:3	1.2 (1.0, 1.4)

n=2 for all the above values; values in parentheses are minimum and maximum values; nd not detected

Source: Finke (2002).

As for other insects, CP contents of field cricket (*Gryllus testaceus*) and Mormon cricket (*Anabrus simplex*) are high (*ca* 60%) and they contain 10 to 13% lipids (Tables 23). Ca content in Mormon cricket is low (2 mg/kg DM). Lysine content is lower in field cricket than in Mormon cricket, while the level of sulphur-containing amino acids (methionine plus cystine) is higher in field cricket (Tables 24 and 25).

Table 23. Chemical composition of field cricket (n = 1) and Mormon cricket (n = 4)

	Crude protein (% in DM)	**Crude fibre (% in DM)**	**Ether extract (% in DM)**	**Ash (% in DM)**
Field cricket	58.1	-	10.3	3.0
Mormon Cricket	59.8 ± 4.1 (56.0, 65.4)	8.2 ± 1.1 (7.4, 9.8)	13.3 ± 5.0 (7.9, 19.9)	6.5 ± 1.9 (4.9, 9.0)

DM dry matter; values are mean ± standard division; values in parentheses are minimum and maximum values; Gross energy = 23.0 MJ/kg DM

Sources : DeFoliart et al., 1982; Nakagaki et al., 1987 ; Wang Dun et al., 2005.

Table 24. Amino acid composition of field cricket

Amino acids	**g/16 g Nitrogen**
Alanine	5.6
Arginine	3.7
Aspartic acid	6.3
Cystine	1.0
Methionine	1.9
Lysine	4.8
Isoleucine	3.1
Leucine	5.5
Phenylalanine	2.9
Threonine	2.8
Glutamic acid	9.1
Histidine	1.9
Proline	4.5
Serine	3.7
Glycine	3.6
Tyrosine	3.9
Valine	4.4

n = 1 for all the above values

Source : Wang Dun et al. (2005).

Table 25. Amino acid composition of Mormon cricket

Amino acids	g/16 g Nitrogen
Alanine (n=1)	9.5
Arginine (n=2)	5.3 (4.5, 6.0)
Aspartic acid (n=1)	8.8
Cystine (n=1)	0.1
Methionine (n=2)	1.4 (1.3, 1.5)
Lysine (n=2)	5.9 (5.6, 6.2)
Isoleucine (n=2)	4.8 (4.2, 5.3)
Leucine (n=2)	8.0 (7.3, 8.6)
Phenylalanine (n=2)	2.5 (2.2, 2.8)
Threonine (n=2)	4.2 (3.5, 4.8)
Tryptophan (n=2)	0.6 (0.5, 0.6)
Glutamic acid (n=1)	11.7
Histidine (n=2)	3.0 (2.6, 3.3)
Proline (n=1)	6.2
Serine (n=1)	4.9
Glycine (n=1)	5.9
Tyrosine (n=2)	5.2 (4.1, 6.2)
Valine (n=3)	6.0 $\pm$ 0.6 (5.5, 6.6)

Values in parentheses are minimum and maximum values

Sources : DeFoliart et al., 1982; Nakagaki et al., 1987.

5.2 Nutritional value for different animal species

Orthoptera, like other insects, are highly nutritious and contain high amounts of protein. Various grasshopper, katydid and cricket species are already used for raising pets and zoo animals and have been investigated for livestock feeding. Particularly, the availability of large quantities of dead locusts resulting from locust outbreaks make them a good potential feed for livestock, especially poultry. Locust meal has been proposed as a poultry feed since 1930s. Poultry are also a means to control locust and grasshopper populations. Since 2000, the development of aquaculture in Africa and Asia and the search for alternative sources of protein have led to feeding trials on catfish and tilapia using locusts and grasshoppers.

Locusts and other Orthoptera used for livestock feeding are fed live (free-range chickens, pets, zoo animals) or dried and ground (broilers, fish). Sometimes they are boiled before drying.

5.2.1 Livestock

Pigs. Information on feeding Orthoptera to pigs is limited and ancient. In Eastern Africa, dried red locusts (*Nomadacris septemfasciata*) fed to pigs in a mixed diet resulted in a satisfactory growth rate, but the fresh meat and bacon both had a definite fishy taint. Removal of the locust meal from the diet, three weeks prior to slaughter, reduced the taint but did not eliminate it (Hemsted, 1947).

Free-range chickens. The rearing of free-range chickens has been proposed as a means to control grasshopper populations. Furthermore, chasing a food source increases poultry movement, enabling them to forage further and exhibit a wider range of natural behaviour (Khusro et al., 2012). In the Philippines, it has been reported that free-range chickens fed on grasshoppers have a preferred taste and have a higher market price than those fed on conventional commercial feed (Khusro et al., 2012). In the Tibetan Plateau, free-range chickens reared on grassland containing a large population of grasshoppers had lower live weights, including lower breast, wing, thigh and drum weights, and higher dressing percentage and breast percentage compared with chickens fed a soymeal-maize diet. Breast meat had higher redness, shear force and protein content, and lower pH, cooking loss, moisture and fat content. Breast and thigh meats showed no treatment effect on colour and juiciness, but higher scores for chewiness, flavour, aroma and overall appreciation, and lower scores for tenderness were observed (Sun Tao et al., 2013). The meat from free-range grasshopper-fed broilers had lower cholesterol but higher concentrations of total lipid and phospholipids (Sun Tao et al., 2012a). Higher antioxidative potential and longer storage life have also been observed (Sun Tao et al., 2012b).

Broilers. An early study in the Philippines reported that locust meal was not as efficient but was as palatable as fishmeal (Fronda, 1935) when fed to broilers. More recent studies have tried to replace a part of fishmeal with locust and grasshopper meal and found that such partial substitution is generally suitable. In Nigeria, broilers (1-28 days) given desert locust meal (*Schistocerca gregaria*) as a substitute for fishmeal, replacing 50% fishmeal protein with locust meal (1.7% in the diet), resulted in higher body weight gain, feed intake and feed conversion ratio (Adeyemo et al., 2008). In China, meal from the grasshopper *Acrida cinerea* could replace 20% and 40% fishmeal in broiler diets with similar growth rate and feed consumption as the control diet (Liu ChanMin et al., 2003). In Nigeria, grasshopper meal (unspecified species) at the inclusion levels of 2.5 to 7.5% (weight basis) in broiler diets (1-49 days) depressed weight gain and feed efficiency, though it increased the protein content of the carcass (Ojewola et al., 2003). In a later study, grasshopper meal included at 2.5% in the diet was found to be a suitable and cheaper substitute for imported fishmeal (100% replacement on weight basis) though the overall diet contained slightly less protein (22.2% *vs.* 22.8%)(Ojewola et al., 2005).

Several workers have studied the value for broilers of Mormon cricket (*Anabrus simplex*), a swarming American katydid. Broilers (1-21 days) fed a diet of 62% maize grain and 30% cricket meal had better growth than broilers fed a control diet based on maize, fishmeal and meat and bone meal. Amino acid supplementation did not improve performance. Also palatability was not affected (DeFoliart et al., 1982). In a later experiment, maize-cricket diets inwhich soymeal was totally replaced with cricket meal containing, as fed, 28% (1-3 weeks), 22% (4-6 weeks) and 18% (7-8 weeks) crickets were compared with maize-soymeal diets in broilers up to 8 weeks. There were no significant differences in weight gain and feed:gain ratio; and no adverse effect on the taste of the meat from birds fed the maize-cricket diet was observed (Finke et al., 1985). A similar experiment with a diet based on maize and 25% house crickets (*Acheta domestica*) fed to broilers for 2 weeks showed that cricket-based diets led to higher feed: gain ratios than the control (maize-soybean based) diet, at the same protein content in the two diets (Nakagaki et al., 1987). Methionine and arginine were limiting factors in diets based on Mormon crickets and house crickets (Finke et al., 1985; Nakagaki et al., 1987). In China, field cricket (*Teleogryllus mitratus*) could be included up to 15% in the diet (as a partical replacement of soymeal) of 8-20 day broilers without any adverse effects on weight gain, feed intake or gain: feed ratio (Wang Dun et al., 2005).

Japanese quails (Cotornix japonica Japonica). In India, Japanese quail were fed with various diets in which grasshopper meal (*O. hyla*) gradually replaced fishmeal. For a range of growth parameters, the best results were obtained with the diet in which 50% of fishmeal was replaced with *Oxya* meal. Fecundity (i.e. the number of eggs laid per female) was significantly higher compared with the control treatment (Haldar, 2012).

Ruminants. No information seems to be available.

5.2.2 Fish

African catfish (Clarias gariepinus). Desert locust meal (*Schistocerca gregaria*) could be used to substitute up to 25% level of dietary protein in *C. gariepinus* juveniles without significant reduction in growth. Chitin may have contributed to lower performance and feed efficiency when higher substitution rates were used (Balogun, 2011). Meal of adult variegated grasshopper (*Zonocerus variegatus*) could replace up to 25% fishmeal (weight basis) in the diets of *C. gariepinus* fingerlings without any adverse effect on growth and nutrient utilization at the same protein level in the diet. Higher inclusion rates decreased digestibility and performance (Alegbeleye et al., 2012).

Walking catfish (Clarias batrachus). Several studies have investigated the effects of feeding dried Indian grasshoppers (*Poekilocerus pictus*) on the histological and physiological parameters of walking catfish. A 91-day feeding of dried grasshopper-containing diet had no effect on hematological parameters but resulted in a little shrinkage in the gills as well as in a reduction in ovarian steroidogenesis, which may reduce fertility (Johri et al., 2010; Johri et al., 2011a, b).

Nila tilapia (Oreochromis niloticus). Migratory locust meal *(Locusta migratoria*) could replace fishmeal up to 25% in isoproteicdiets of Nile tilapia fingerlings without any adverse effect on the nutrient digestibility, growth performance and haematological parameters (Abanikannda, 2012; Emehinaiye, 2012).

5.3 Potential constraints

Pesticides. Due to their status as agricultural pests, locusts and grasshoppers may be sprayed with insecticides in governmental control programmes or by farmers, resulting in significant amounts of residues in consumed insects. These risks are of major concern in the traditional practices of harvesting in the wild and consuming them where the control of chemical applications is difficult (van Huis et al., 2013). For example, high concentrations of residues of organophosphorus pesticides were detected in locusts collected for food in Kuwait after the outbreak of 1988/1989 (Saeed et al., 1993). In Korea, the mandatory use of pesticides in rice fields led to a decline in traditional grasshopper consumption in the 1970s, which resumed in the 1990s with the rise in organic rice farming. In Mali, the increasing use of pesticides in cotton farming has led to a decline in grasshopper consumption by children in rural areas, with negative consequences on the protein intake of these children (van Huis et al., 2013). One study showed that broiler chicks fed locusts that had been sprayed with an insecticide had a lower intake than chicks fed unsprayed locusts (Gibril, 1997).

Lead contamination. In California, an outbreak of lead poisoning in 2000 in the Mexican community was traced back to the consumption of chapulines grasshoppers (*Sphenarium*) imported from Mexico to the United States. It is suspected that the insects, which contained up to 2500 ppm of lead, had bioaccumulated lead from the tailings of silver mines in Oaxaca (Handley et al., 2007).

Presence of spines. The presence of large spines on the tibia of grasshoppers and locusts may cause intestinal constipation, which has been shown to be fatal in monkeys after locust outbreaks and has occasionally required surgery in humans. Grinding or removing the legs and wings is therefore recommended prior to consumption (van Huis et al., 2013).

6 Silkworm pupae meal

Other common names are: silkworm pupae, silkworm meal, silk worm meal, spent silkworm pupae, defatted silkworm pupae meal, deoiled silkworm pupae meal, non-defatted silkworm pupae meal, non-deoiled silkworm pupae meal, Eri silkworm pupae meal, Muga silkworm pupae meal. A number of species of silkworm are known: *Bombyx mori* Linnaeus, 1758 [Bombycidae]; *Antheraea assamensis* Helfer, 1837; *Antheraea mylitta* (Drury, 1773); *Antheraea paphia* Linnaeus, 1758; *Samia cynthia ricini* [Saturniidae]

Silkworms are the caterpillars of moth species raised for the production of silk. The world's 90% production results from the cocoons of the domesticated mulberry silkmoth *Bombyx mori*, a Bombycidae moth. Silk is also produced from other domesticated or wild Saturnidae moth species, notably the Eri silkmoth *Samia cynthia ricini*, the Assam silkmoth *Antheraea assamensis*, the tussore (or tussah) moth *Antheraea mylitta* and the small tussore *Antheraea paphia* (Mishra et al., 2003; Longvah et al., 2011). When the silkworm enters the pupa phase, it builds a protective cocoon made of raw silk. At the end of pupation, the pupa releases an enzyme that creates a hole in the cocoon and the moth emerges. In order to produce silk, the pupae are killed by boiling, drying or soaking in NaOH before they produce the enzyme (Datta, 2007; Jintasataporn, 2012). The spent pupae are produced in large quantities and are a major by-product of silk production (Datta, 2007). For 1 kg of raw silk, 8 kg of wet pupae (2 kg of dry pupae) are produced (Patil et al., 2013).

Spent silkworm pupae is a waste material often discarded in the open environment or used as a fertilizer (Wei ZhaoJun et al., 2009). It can be extracted to yield a valuable oil used in industrial products such as paints, varnishes, pharmaceuticals, soaps, candles, plastic and biofuels (Trivedy et al., 2008). The extracted meal is sometimes used for the production of chitin, the long-chain polymer of Nacetylglucosamine which is the main component of the exosqueleton (Suresh et al., 2012). Silkworm pupae have long been part of human food in Asian silk-producing countries, and is considered as a delicacy in regions of China (Luo Zhi-Yi, 1997), Japan (Mitsuhashi, 1997), Thailand (Yhoung-Aree et al., 1997) and India (Longvah et al., 2011), among others. Due to its high protein content, silkworm pupae meal has been found to be suitable as a livestock feed, notably in monogastric species (poultry, pigs and fish), and also in ruminants (Trivedy et al., 2008).

Fresh spent silkworm pupae spoils rapidly due to its high water content and spent pupae are generally sun-dried and ground (Wijayasinghe et al., 1977; Usub et al., 2008; Jintasataporn, 2012). The degradation of mulberry-fed silkworm pupae produces a foul smell, which has been attributed to the presence in mulberry leaves of compounds that might be sequestered by silkworms, including essential oils, flavenoids, and terpenoids. This bad odour has been linked to palatability of the silkworm pupae to animals (Rao, 1994; Finke, 2002). Defatted silkworm pupae meal is less perishable and has a higher protein content than the non-defatted meal (Blair, 2008). Ensiling also increases the shelf life of silkworm pupae meal and good quality silage has been obtained when ensiling with molasses, propionic acid or curd as lactic acid culture (Rangacharyulu et al., 2003; Yashoda et al., 2008). Spent silkworm pupae should be ground to assure more uniform mixing in rations (Göhl, 1982).

Silkworm litter (or silkworm dregs), another by-product of silkworm rearing, is a mixture of excreta, sloughs (moulting residues) and mulberry leaves (Chen YaoWang, 1989). The digestibility of the litter is about 55% (Patil et al., 2013)

The world production of reelable silkworm cocoons was about 485,000 tonnes in 2011. By substracting the amount of raw silk (161,000 tonnes), it can be assumed that 324,000 tonnes of fresh pupae (65,000 tonnes dry pupae) were produced in 2011 (FAO, 2012). Note that this estimate is much lower than the official statistics from China, where a figure of 440,000 tonnes of dry pupae in 2009 has been cited (Wei

ZhaoJun et al., 2009). The main silk producers are China, India, Uzbekistan, Brazil, Thailand and Vietnam (FAO, 2012).

Spent silkworm pupae are a highly degradable product. In silk production areas, the disposal of large quantities of pupae can cause serious environmental problems (Wang Jun et al., 2010). The utilization of this resource for feed and food or for the production of valuable biological substances such as chitin, protein, oil and fatty acids (α-linolenic acid) is a way to reduce the environmental impact of silk production.

6.1 Chemical constituents

Silkworm pupae meal is a protein-rich feed ingredient with a high nutritional value. Its CP content ranges from 52 to 72 % (Table 26) while for the defatted meal it can be higher than 80% (Table 29). As for other insects, silkworm meal also has low Ca and low Ca:P ratio (Tables 27). The lysine (6-7% in 100 g CP) and methionine plus cystine leves of approximately 4% (Tables 28 and 30) are particularly high. However, the true protein (calculated as the sum of amino acids) in silkworms was found to correspond to only 73% of the CP content (Finke, 2002), which was explained by the presence of chitin, since this component includes nitrogen. On the other hand, the chitin content of pupae meal is relatively low, about 3-4% DM (Finke, 2002; Suresh et al., 2012). The presence of chitin and insoluble protein may also explain the ADF values of 6-12% in DM (Finke, 2002; Ioselevich et al., 2004). Non-defatted pupae meal is rich in fat, up to 37%. Silkworm oil contains a high percentage of polyunsaturated fatty acids, notably linolenic acid (18:3), with values ranging from 11 to 45% of the total fatty acids (Rao, 1994; Ioselevich et al., 2004; Usub et al., 2008).

Table 26. Chemical composition of silkworm pupae meal (non-defatted)

Crude protein (% in DM), n=10	Crude fibre (% in DM), n=6	Ether extract (% in DM), n=10	Ash (% in DM), n=11
60.7 ± 7.0 (51.6, 70.6)	3.9 ± 1.1 (2.5, 5.8)	25.7 ± 9.0 (6.2, 37.1)	5.8 ± 2.4 (3.3, 10.6)

DM, dry matter; n = 9 for all the values; values are mean ± standard deviation; values in parentheses are minimum and maximum values; Gross energy = 25.8 MJ/kg DM

Sources : Coll et al., 1992; Fagoonee, 1983; Göhl, 1982; Gowda et al., 2004; Hossain et al., 1993; Hossain et al., 1997; Ioselevich et al., 2004; Jintasataporn, 2012; Longvah et al., 2011; Narang et al., 1985; Rao, 1994.

Table 27. Mineral content of silkworm pupae meal (non-defatted) (all values in g/kg DM except Cu, Mn, Fe and Zn which are in mg/kg DM)

Ca, n=6	P, n=6	Mg, n=3	Cu, n=3	Mn, n=2	Fe, n=3	Zn, n=3
3.8 ± 3.0 (0.7, 8.4)	6.0 ± 2.3 (1.9, 8.5)	3.7 ± 2.5 (1.9, 6.5)	15 ± 12 (2, 25)	18.0 (9, 28)	326.0 ± 67 (262, 395)	224.0 ± 126 (79, 310)

DM, dry matter; values are mean ± standard deviation; values in parentheses are minimum and maximum values

Sources : Coll et al., 1992; Göhl, 1982; Gowda et al., 2004; Jintasataporn, 2012; Longvah et al., 2011; Rao, 1994.

Silkworm litter appears to have an extremely variable composition, with CP values of between 15 and 58% in dry matter (Chen YaoWang, 1989; Patil et al., 2013).

Table 28. Amino acid composition of silkworm pupae meal (non-defatted)

Amino acids	**g/16 g Nitrogen**
Alanine	5.8 (5.5, 6.1)
Arginine	5.6 (4.4, 6.8)
Aspartic acid	10.4 (9.9, 10.9)
Cystine	1.0 (0.5, 1.4)
Methionine	3.5 (2.3, 4.6)
Lysine	7.0 (6.5, 7.5)
Isoleucine	5.1 (4.4, 5.7)
Leucine	7.5 (6.6, 8.3)
Phenylalanine	5.2 (5.1, 5.2)
Threonine	5.1 (4.8, 5.4)
Tryptophan	0.9
Glutamic acid	13.9 (12.9, 14.9)
Histidine	2.6 (2.5, 2.7)
Proline	5.2 (4.0, 6.5)
Serine	5.0 (4.7, 5.3)
Glycine	4.8 (4.6, 4.9)
Tyrosine	5.9 (5.4, 6.4)
Valine	5.5 (5.4, 5.6)

n=2 for all values except for tryptophan (n=1); values in parentheses are minimum and maximum values

Sources: Longvah et al., 2011; Rao, 1994.

Table 29. Chemical composition of silkworm pupae meal (defatted)

Crude protein (% in DM), n=10	**Crude fibre (% in DM), n=3**	**Ether extract (% in DM), n=8**	**Ash (% in DM), n=8**	**Ca (g/kg DM), n=4**	**P (g/kg DM), n=4**
75.6 ± 10.8 (48.9, 83.3)	6.6 ± 3.1 (4.3, 10.2)	4.7 ± 2.7 (1.0, 8.5)	6.8 ± 4.1 (2.1, 14.6)	4.0 ± 3.6 (1.0, 9.1)	8.7 ± 4.8 (3.3, 15.0)

DM, dry matter; Gross energy = 22.0 ± 0.4 MJ/kg DM (n=3); values are mean ± standard deviation; values in parentheses are minimum and maximum values

Sources : Hossain et al., 1997; Jintasataporn, 2012; Khan et al., 1971; Lakshminarayana et al., 1971; Lin et al., 1983.

Table 30. Amino acid composition of silkworm pupae meal (defatted)

Amino acids	g/16 g Nitrogen
Alanine	4.4 + 0.2 (4.0, 4.6)
Arginine	5.1 + 0.3 (4.7, 5.4)
Aspartic acid	7.8 + 0.7 (6.9, 8.6)
Cystine	0.8 + 0.5 (0.3, 1.4)
Methionine	3.0 + 0.4 (2.3, 3.4)
Lysine	6.1 + 0.4 (5.8, 6.7)
Isoleucine	3.9 + 0.2 (3.7, 4.1)
Leucine	5.8 + 0.2 (5.6, 8.0)
Phenylalanine	4.4 + 0.3 (4.1, 4.8)
Threonine	4.8 + 0.3 (4.5, 5.2)
Tryptophan	1.4 + 0.2 (1.2, 1.6)
Glutamic acid	8.3 + 0.7 (7.5, 8.9)
Histidine	2.6 + 0.1 (2.4, 2.8)
Proline	5.2 (4.0, 6.5)
Serine	4.5 + 0.2 (4.2, 4.7)
Glycine	3.7 + 0.3 (3.4, 3.1)
Tyrosine	5.5 + 0.2 (5.3, 5.8)
Valine	4.9 + 0.2 (4.6, 5.1)

Values are mean + standard deviation; values in parentheses are minimum and maximum values; n=5 for all values except cystine (n=4)

Source: Lin et al. (1983).

6.2 Nutritional value for different animal species

6.2.1 Livestock

Ruminants. Silkworm meal is a very valuable protein supplement for ruminant animals, due to its high undegradable protein content and favourable amino acid pattern. Limitations in its use as ruminant feed result from the high oil content. Therefore, fat extraction of silkworm meal is of interest when fed in a large amount (Ioselevich et al., 2004).

Effective *in situ* nitrogen degradability of silkworm meal is quite low. Reported effective degradability values (5%/h outflow rate) for non-defatted silkworm pupae were 29% and 25% (Chandrasekharaiah et al., 2002; Ioselevich et al., 2004) and 20% for defatted meal (Chandrasekharaiah et al., 2004), resulting in high amounts of undegradable protein, notably for the defatted meal, which is richer in protein. Lysine and methionine, which are considered to be the two major limiting amino acids for milk production, have both a low *in situ* disappearance of 26% (24 h incubation, 5%/h outflow rate), which means that the bypass protein fractions of silkworm pupae are good sources of lysine and methionine for ruminants (Sampath et al., 2003). However, the undegradable protein fraction has a relative low intestinal protein digestibility of 53%, as estimated by *in vitro* pepsin-pancreatin solubility (Ioselevich et al., 2004). Further studies are required to better understand the rumen and post-rumen protein digestibility of the silkworm meal protein.

Non-defatted silkworm meal could safely replace 33% of groundnut cake (weight basis) in fattening diets for Jersey calves without decreasing performance, resulting in a cheaper feed. The protein digestibility of the silkworm meal-based diet was higher than that of the groundnut cake diet (Narang and Lal, 1985). In lambs fed a basal diet of barley and hay (75:25), the isonitrogenous substitution of a potato protein supplement with non-defatted silkworm meal resulted in similar increases in nitrogen and energy retention (Ioselevich et al., 2004). The CP digestibility of defatted Tussore silkworm pupae fed with wheat straw and molasses to sheep was about 70% (Khan and Zubairy, 1971).

Pigs. Limited information is available on the utilization of silkworm pupae in pigs. Two experiments showed that silkworm pupae meal was a good replacer of the traditional protein sources. In Brazil, it was possible to replace up to 100% of soymeal in diets for growing and finishing pigs with non-defatted silkworm meal with no adverse effect on growth performance and carcass characteristics. There was a negative effect on intake when the substitution rate was higher than 50%, which was attributed to the higher energy density of the diet or to a lower palatability. However, the lower intake was compensated by a better feed conversion rate, which may have been due to the higher lysine content of the silkworm-based diet (Coll et al., 1992). In India, silkworm meal could fully replace fishmeal in the diet of growing and finishing pigs without altering carcass and meat quality and blood parameters (Medhi et al., 2009a, b; Medhi, 2011).

Silkworm litter can be used in pig diets. The recommended inclusion rate is about 7% and should not exceed 10% (Chen YaoWang, 1989; Wang et al., 2007).

Poultry. Silkworm pupae meal is a valuable protein source that can be used in poultry feeding, though it is of slightly lower quality than fishmeal. High amino acid digestibilities (lysine 94%, methionine 95%) were observed in geese (Penkov et al., 2002). The ME was determined to be 10.2 MJ/kg DM. Unless otherwise specified, the silkworm pupae meal used in the studies cited below was not defatted, though this is not always clear from the papers or abstracts (Tables 31 and 32).

Laying hens and breeders. Silkworm meal seems to be well accepted by laying hens (Saikia et al., 1971; Joshi et al., 1979; Joshi et al., 1980). One study found that silkworm pupae meal was detrimental to the breeding performance of breeder males (Mahanta et al., 2004) (Table 31).

Table 31. Nutritional attributes of silkworm meal in laying hens

Country	**Trial**	**Results**	**Reference**
India	Layer chicks: substitution for 0-100% fish meal (up to 6% in diet)	Reduction of intake and weight gain in diets based on 50-100% substitution of fish meal by silkworm meal	Deshpande et al., 1996
India	Layer chicks: substitution for 0-100% fish meal	Deoiled silkworm meal could replace 100% fish meal	Virk et al., 1980
India	Laying hens: comparison done with a number of other alternative feeds	Best technical and economic performance (feed-to-egg conversion ratio, egg size, shell thickness, grading, light yellow yolk, no mortality, feed cost, cost per dozen eggs)	Saikia et al., 1971
India	Layer chicks: 6 to 8% silkworm meal replacing a protein concentrate	Profitability, growth and egg production performance higher with 6% silkworm meal in diet	Khatun et al., 2005
Bangladesh	Substitution 0-100% of fish meal	Breeder males: At 50 and 100% of substitution, detrimental effects of muga silkworm meal on certain breeding performance indicators (ejaculate volume, quantity and quality of spermatozoa)	Mahanta et al., 2004

Table 32. Nutritional attributes of silkworm meal in broilers

Country	Trial	Results	Reference
Thailand	Substitution 0-100% of fish meal (0-20% in diet)	A mixture of defatted and non-defatted silkworm meal could replace fishmeal at a 10% inclusion rate in the diet with little adverse effect on broiler growth, muscle mass and taste. Higher rates of inclusion were detrimental to feed conversion and carcass muscle	Jintasataporn, 2012
India	Substitution 0-50% of fish meal	50% replacement of fish meal (5% diet) had an adverse effect on growth performance and feed efficiency. This effect could be overcome with salt and/or mineral supplementation	Reddy et al., 1991
Mauritius	Substitution 0-100% of fish meal	Total replacement of fish meal had an adverse effect on growth performance but 50% replacement had no adverse effect	Fagoonee, 1983b
Turkey	Substitution 50-100% of fish meal or meat and bone meal	Detrimental to weight gain and feed efficiency	Tas, 1983
India	Substitution 0-100% of fish meal	Total replacement decreased feed use efficiency, while 50% replacement has no adverse effect even without Ca and P supplementation	Purushothaman and Thirumalai, 1995
India	Substitution 0-100% of fish meal	Silkworm meal replaced fish meal without adverse effects. The best performance was obtained with 50% replacement of fish meal by silkworm pupae and supplemented with enzymes	Konwar et al., 2008
India	Substitution 0-100% of fish meal	No adverse effect of muga silkworm meal addition at 100% substitution	Sapcota et al., 2003
India	Substitution 0-100% of fish meal	Muga silkworm meal replacing 100% fish meal gave the best economic gains	Sheikh and Sapcota, 2007
India	Substitution 0-100% of fish meal	100% fish meal diet resulted in a higher live weight gain but the 50% replacement of fish meal by silkworm diet gave higher nitrogen and calcium retention	Sheikh and Sapcota, 2010
India	Substitution 0-100% of fish meal	100% replacement of fishmeal with muga silkworm meal had no adverse effect on carcass characteristics	Sheikh et al., 2005
India	Substitution 0-100% of fish meal	Tussore silkworm meal could replace 50% of fish meal while increasing the profit margin due to its much lower cost	Seema Sinha et al., 2009;Dutta et al., 2012
India	Substitution 0-100% of fish meal	Fermented silkworm pupae or fresh silkworm pupae could replace fish meal, resulting in a better feed conversion rate and an absence of fishy taint in the meat	Rao et al., 2011

Broilers. Experiments have shown that replacing 50% (by weight basis) of the main protein source (fishmeal in most of the experiments) with silkworm meal is usually safe, though mineral supplementation may be required (Table 31). Total replacement is sometimes possible but tends to lower the performance. Inclusion rates in the diets are typically in the 5-6% range. One report indicated a growth stimulating effect in growing chicks, which the authors attributed to the ecdysteroid activity (a hormone involved in metamorphosis of the pupae) (Fagoonee, 1983a) though this has not been confirmed since. Treating deoiled silkworm meal with 70% acetone for 12 h was shown to improve broiler performance (Venkatchalam et al., 1997).

Rabbits. Dried silkworm meal could totally replace soymeal in balanced diets for growing rabbits without any adverse effects (Carregal and Takahashi, 1987). Silkworm meal at 7% in diet was included in the control diet for a study that evaluated a new variety of rapeseed meal in China (Liu et al., 1987), suggesting that the silkworm meal is a traditional ingredient in rabbit feeds in China.

6.2.2 Fish

Silkworm pupae meal is a valuable protein source in many fish species.

Carps (*Cyprinus carpio*). On 100% replacement of fishmeal protein with silkworm meal, similar performance (growth and feed conversion) was observed in carp (Nandeesha et al., 1990; Rahman et al., 1996). In a comparison between silkworm pupae meal and plant leaf meals (alfalfa and mulberry), feed conversion efficiency, nutrient digestibilities and nutrient retention were better for diets based on silkworm meal than for diets based on plant leaf meals (Swamy and Devaraj, 1994).

Fermented silkworm pupae silage or untreated fresh silkworm pupae paste were incorporated in carp feed formulations replacing fishmeal in a polyculture system containing the Indian carps (*Catla catla*), mrigal carps (*Cirrhinus mrigala*), rohus (*Labeo rohita*) and silver carps (*Hypophthalmychthys molitrix*).

Survival rate, feed conversion ratio and specific growth rate were better for fermented silkworm pupae silage fed carp than for carp fed untreated silkworm pupae or fishmeal (Rangacharyulu et al., 2003). In rohu, non-defatted silkworm pupae and defatted silkworm pupae resulted in significantly higher protein digestibility values than fishmeal (Hossain et al., 1997).

Silver barb (*Barbonymus gonionotus*). In silver barb fingerlings, highest growth performance was observed in fish fed a diet replacing about 38% of total dietary protein by silkworm pupae meal (Mahata et al., 1994).

Mahseer (Tor khudree). Mahseer fingerlings fed a diet containing 50% defatted silkworm pupae at 5% of body weight had a better growth and survival than fingerlings fed no or lower amounts of silkworm pupae (Shyama and Keshavanath, 1993).

Tilapia (Oreochromis mossambicus). Tilapia was able to utilize the protein of both defatted and non-defatted silkworm meal with high apparent protein digestilibility of 85-86% (Hossain et al., 1992).

Asian stinging catfish (Heteropneustes fossilis). Silkworm pupae meal could be used as a substitute for fishmeal at up to 75% of protein in Asian stinging catfish diets without adverse effect on growth (Hossain et al., 1993).

Walking catfish (Clarias batrachus). Non-defatted silkworm pupae meal was found to be a suitable fishmeal substitute in diets for walking catfish. Digestibility of the CP in silkworm meal was found to be similar to that in fishmeal (Borthakur and Sarma, 1998a). Walking catfish fingerlings fed silkworm meal had slightly lower specific growth rate and poorer feed conversion ratio (2.81 *vs.* 2.45) than fingerlings fed on fishmeal (Borthakur and Sarma, 1998b).

Japanese sea bass (Lateolabrax japonicus). In Japanese sea bass, the energy digestibility (73%) of non-defatted silkworm pupae meal was lower than that of poultry by-product meal, feather meal, blood meal and soymeal but comparable to that of meat and bone meal. CP digestibility (85%) was also lower than that of poultry by-product meal, blood meal and soymeal but was comparable with that of feather meal and higher than that of meat and bone meal (Ji WenXiu et al., 2010).

6.2.3 Crustaceans

Shrimp growth trials showed that digestive efficiency was reduced when silkworm meal was used to replace fishmeal (Sumitra-Vijayaraghavan et al., 1978).

6.2.4 Other species

Abalone (Haliotis discus hannai Ino.). In juvenile abalones, a combination of soymeal (29%, DM basis) and silkworm pupae meal (16.9%, DM basis) could totally replace fishmeal, resulting in slightly higher survival and growth performance (Cho SungHwoan, 2010).

7 **A synthesis and conclusions**

Table 33 compares the CP and lipid contents in insects meals discussed in this paper with those in soymeal and fishmeal. Average values from the previous sections have been taken for the discussion. It is important to note that these values are average of multiple values, collated from a number of publications. The CP contents are high, varying from 42 to 63%, which are of the same order as is in soymeal but are slightly lower than that in fishmeal. After defatting, the CP content in insect meals is expected to be higher than those of both the conventional resources – soymeal and fishmeal – generally used in the preparation of livestock and fish diets respectively (Table 33). Some insect meals, for example (black soldier fly larvae, housefly maggot meal, mealworm, silkworm) contain as high as 36% oil, which can be isolated and used for the preparation of biodiesel; and the rest of the defatted meal, being rich in CP, could find a place as an invaluable protein-rich resource in the feed industry. Presence of high levels of lipids in the meals can also decrease fibre digestion in the rumen and is also not good for optimum rumen fermentation, and hence defatted insect meals would be an ideal choice for ruminants. Insect meals (e.g. black soldier fly larvae) contain high levels of ash and hence their higher levels of inclusion in the diet, especially of monogastrics, can decrease its intake and cause other adverse effects.

For growing pigs and broilers the major limiting amino acids are lysine and methionine. The deficiency of tryptophan and threonine could also decrease the performance of these animals. Amino acid compositions of various insect resources and other conventional feed resources are given in Table 34. Methionine levels in all insect meals are higher than that in soymeal, while the levels of sulphur-containing amino acids (methionine + cystine) are lower in black soldier fly larvae, mealworm, house cricket and mormon cricket than in soymeal. Lysine is lower in mealworm, locust meal, house cricket and mormon cricket than in soymeal. Lysine levels are adequate in black soldier fly larvae, housefly maggot and silkworm pupae meals. Overall levels of essential amino acids in insect meals are good; most essential amino acid levels in silkworm pupae meal and black soldier fly larvae being higher than in soymeal or the FAO Reference Protein. A 50:50 mixture of black soldier fly larvae and housefly maggot meals would provide a balanced amino acid composition for use in livestock feed as soymeal replacers. Arginine is also considered an essential amino acids for laying hens and the level of this amino acid in all insect meals was lower than in soymeal, suggesting its addition in the diets of laying hens containing these insect meals. Other insect meals having lower levels of essential amino acids could also be invaluable soymeal replacer in livestock diets when supplemented with synthetic amino acids. Synthetic amino acids are low-cost additives, which now-a-days are commonly used in the preparation of compound feeds by the feed industry.

For fish species, fishmeal could be considered as an ideal feed ingredient for optimal growth. The supplementation of synthetic lysine and tryptophan with almost all insect meals and of threonine and

Table 33. Main chemical constituents in insect meals vis-à-vis fishmeal and soymeal

Constituents % in DM)	**Black soldier fly larvae**	**Housefly maggot meal**	**Meal-worm**	**Locust meal**	**House cricket**	**Mormon cricket**	**Silkworm pupae meal**	**Silkworm pupae meal (defatted)**	**Fishmeal**	**Soymeal**
Crude protein	42.1 (56.9)	50.4 (62.1)	52.8 (82.6)	57.3 (62.6)	63.3 (76.5)	59.8 (69.0)	60.7 (81.7)	75.6	70.6	51.8
Lipid	26.0	18.9	36.1	8.5	17.3	13.3	25.7	4.7	9.9	2.0
Calcium	7.56	0.47	0.27	0.13	1.01	0.20	0.38	0.40	4.34	0.39
Phosphorus	0.90	1.60	0.78	0.11	0.79	1.04	0.60	0.87	2.79	0.69
Ca:P ratio	8.4	0.29	0.35	1.18	1.28	0.19	0.63	0.46	1.56	0.57

Values in parentheses are calculated values of the defatted meals

Table 34. Amino acid composition (g/16 g nitrogen) of insect meals versus FAO reference dietary protein requirement values, soymeal and fishmeal

Amino acids	**Black soldier fly larvae**	**Housefly maggot meal**	**Meal-worm**	**Locust meal**	**House cricket**	**Mormon cricket**	**Silkworm pupae meal**	**Silkworm pupae meal (defatted)**	**Fishmeal**	**Soymeal**	**FAO Reference protein for 2-5 year old child**
Essential											
Methionine	2.1	2.2	1.5	2.3	1.4	1.4	3.5	3.0	2.7	1.32	2.50(1)
Cystine	0.1	0.7	0.8	1.1	0.8	0.1	1.0	0.8	0.8	1.38	
Valine	8.2	4.0	6.0	4.0	5.1	6.0	5.5	4.9	4.9	4.50	3.50
Isoleucine	5.1	3.2	4.6	4.0	4.4	4.8	5.1	3.9	4.2	4.16	2.80
Leucine	7.9	5.4	8.6	5.8	9.8	8.0	7.5	5.8	7.2	7.58	6.60
Phenylalanine	5.2	4.6	4.0	3.4	3.0	2.5	5.2	4.4	3.9	5.16	6.30(2)
Tyrosine	6.9	4.7	7.4	3.3	5.2	5.2	5.9	5.5	3.1	3.35	
Histidine	3.0	2.4	3.4	3.0	2.3	3.0	2.6	2.6	2.4	3.06	1.90
Lysine	6.6	6.1	5.4	4.7	5.4	5.9	7.0	6.1	7.5	6.18	5.80
Threonine	3.7	3.5	4.0	3.5	3.6	4.2	5.1	4.8	4.1	3.78	3.40
Tryptophan	0.5	1.5	0.6	0.8	0.6	0.6	0.9	1.4	1.0	1.36	1.10
Non-essential											
Serine	3.1	3.6	7.0	5.0	4.6	4.9	5.0	4.5	3.9	5.18	-
Arginine	5.6	4.6	4.8	5.6	6.1	5.3	5.6	5.1	6.2	7.64	-
Glutamic acid	10.9	11.7	11.3	15.4	10.4	11.7	13.9	8.3	12.6	19.92	-
Aspartic acid	11.0	7.5	7.5	9.4	7.7	8.8	10.4	7.8	9.1	14.14	-
Proline	6.6	3.3	6.8	2.9	5.6	6.2	5.2	-	4.2	5.99	-
Glycine	5.7	4.2	4.9	4.8	5.2	5.9	4.8	3.7	6.4	4.52	-
Alanine	7.7	5.8	7.3	4.6	8.8	9.5	5.8	4.4	6.3	4.54	-

Notes: (1) Methionine plus cystine; (2) Phenylalanine plus tyrosine.

sulphur-containing amino acids with all insect meals except silkworm pupae meal would be required for the optimum growth.

The digestibility of insect proteins and their utilization *in vivo* have also been good. Apparent faecal digestibility of black soldier fly larvae and soymeal in male growing pigs was similar (76 vs 77% respectively) (Newton et al., 1977). Studies conducted using housefly meal in broilers have also shown variable results. Pretorius (2011) reported apparent faecal CP digestibility of 69% whereas Hwangbo et al. (2009) reported a higher value of 98.5%. The former study reported amino acid digestibilities of > 90% while the CP digestibility was much lower, which might be attributed to indigestibility of chitin-N and/or ADF bound-N.

Ca and P values are important for poultry and pig production as well as for milk production from large and small ruminants. Black soldier fly larvae are rich in Ca (7.56%) with highest Ca: P ratio of 8.4, while for other insect meals the Ca levels were very low and its supplementation would be required should these be used in animal feed. Ca fortification of the substrate on which the insects are raised also increases the Ca level in the larvae meals (Table 33). Ca: P ratio of 2 is generally considered to be optimum for most livestock feeds, which is far from the Ca:P ratios, varying from 0.19 to 1.18 in insect meals other than that in black soldier fly larvae. In some insects (e.g. housefly maggot meal and Mormon cricket) P levels are particularly high (1.0 to 1.6%).

Fatty acid composition of oils from all the insect meals discussed in this paper is not available. Polyunsaturated fatty acids have a hypocholesterolaemic effects. Increasing levels of polyunsaturated fatty acids in human diet reduce the risk of cardiovascular diseases and chronic pathologies (e.g. cancer, diabetes (Simopoulos, 1999). Deficiencies of essential fatty acids such as linoleic (18:2), linolenic (18:3) and arachidonic (20:4) elicit a number of adverse effects such as growth retardation, dermal symptoms, malabsorption and catabolic diseases. Unsaturated fatty acids (monosaturated plus polyunsaturated) concentrations are high in mealworm, house cricket and housefly maggot meals (60-70%), while this concentration is lowest in black soldier fly larvae (19-37%), suggesting the presence of higher levels of saturated fatty acids in black soldier fly larvae (Table 35). Unsaturated fatty acid levels in soybean oil and sunflower oil are *ca* 85 and 89% respectively (González et al*.,* 2014). In the insect meals, as in the plant oils, linoleic acid concentration is higher than that of alpha-linolenic acid (18:3n–3) (e.g. soybean oil 54 % vs. 6% and sunflower oil 63% vs. 0.2%). Fatty acid composition in black soldier fly can be manipulated by changing the composition of the substrate (St-Hilaire et al., 2007b). On changing the substrate from cow manure to 50: 50 mix of cow manure and fish offal containing omega fatty acids increased the level of omega-3 fatty acid in the larvae from 0.226% to 1.99%. Omega-3 fatty acids are linked to lowering the coronary heart diseases. However, the use of fish offal also increased the levels of saturated fatty acids, from 46.1 to 61.9% which could possibly counteract the beneficial effects of omega-3 fatty acids. The use of fish offal might not be a good option for enhancing the quality of black soldier larvae from health benefitting point of view for humans or monogastric animals but evidence do exist that fatty acid composition in insect meals can be manipulated using wastes containing lipids of different fatty acid composition.

The feeding studies conducted so far have confirmed that the palatability of the insect meals containing diets is good and that these alternate feed resources can replace soybean and fishmeal in the diets of livestock and fish species. Most feeding studies with diets containing insect meals have been conducted on fish and poultry, followed by pigs and then ruminant animals. This is attributed to the limited availability of insect meals. The nutrient utilization and growth studies in pigs and ruminants require a substantial amount of insect meal, and their limited availability allows their evaluation and use in fish or

Table 35. Fatty acid composition of insect lipids

Constituents in (% fatty acids)	Black soldier fly larvae[1]	Housefly maggot meal	Mealworm	House cricket
Saturated fatty acids (%)				
Lauric, 12:0	21.4 [49.3] (42.6)	-	0.5	-
Myristic, 14 :0	2.9 [6.8] (6.9)	5.5	4.0	0.7
Palmitic, 16:0	16.1 [10.5] (11.1)	31.1	21.1	23.4
Stearic, 18:0	5.7 [2.78] (1.3)	3.4	2.7	9.8
Monosaturated fatty acids (%)				
Palmitoleic, 16:1n-7	[3.5]	13.4	4.0	1.3
Oleic, 18: 1n-9	32.1 [11.8] (12.3)	24.8	37.7	23.8
Polyunsaturated fatty acids (%)				
Linoleic, 18:2n-6	4.5 [3.7] (3.6)	19.8	27.4	38.0
Linolenic, 18:3n-3	0.19 [0.08] (0.74)	2.0	1.2	1.2
Eicosapentaenoic, 20:5n-3	0.03 [0] (1.66)	-	-	-
Docosahexaenoic, 22:6n-3	0.006 [0] (0.59)	-	-	-

(1) Values using cow manure as substrate. Round parentheses are the values obtained on using 50% of cow manure and 50% of fish offal as substrate. Square parentheses are values obtained on swine manure as substrate.

poultry diets. Future higher availability of insect meals would provide impetus to the studies on evaluation of these alternate feed resources in ruminant livestock as well.

Studies conducted on including black soldier fly larvae in poultry, pig and fish diets suggest that it could replace soymeal in their diets; however more in-depth studies are required to optimize its levels of inclusion, and at its high levels of inclusion to also optimize the levels of deficient amino acids supplementation. Studies on fish also showed that the aroma and texture of fish do not change on feeding black soldier fly larvae. Processing of these larvae (e.g. cuticle removal, rendering or chopping) appears to increase nutrient availability from the larvae in fish. In shrimps the addition of black soldier fly larvae produced lighter coloured shrimp and also increased economic returns. Acceptability of diets containing these larvae by alligators has been limited.

Backyard chicken and fish can be fed live housefly maggots. Studies conducted in Africa have demonstrated that feeding of live housefly maggots increased growth rate, egg size and egg weight. In poultry a number of studies have been conducted on broilers. Studies on laying hens are limited. In laying hens maggots could replace up to 50% of fishmeal (maggots inclusion: 5% in diet) without any adverse effects; however 100% replacement produced negative effects on egg production. For broilers, the optimum level of their inclusion is generally lower than 10% and methionine supplementation is suggested. In fish species, 25% replacement of fishmeal does not affect growth performance; however higher levels of fishmeal replacement appear to produce adverse effects. Supplementation of amino acids in the diets that are deficient in maggots could increase their levels of inclusion in fish diets.

There is limited information on the use of mealworm in the diets of both broilers and laying hens. The information so far obtained suggest that it could be a valuable replacer of soymeal and fishmeal when supplemented with methionine. As with most other insect meals Ca supplementation would be required for growing chicks. A 10% level of mealworm in the diets of broiler starter diets could be used without any adverse effects. In catfish diet, mealworm can replace 40% of fishmeal. Information on the use of mealworm in the diets of other fish species needs to be generated.

Feeding of grasshopper-containing diets to free-range chickens increased protein and decreased cholesterol content in meat. Higher antioxidant potential and longer shelf life has also been observed. A number of other meat quality parameters were also affected on feeding grasshopper diets. In the Philippines people prefer taste of meat from free-range chickens fed grasshoppers and such chickens are sold at a higher price in the market. It appears that grasshopper meal could be added into the diets of broilers at a level of up to 2.5% (as a substitute for fishmeal). Studies suggest that the Mormon cricket can be incorporated into the broiler diets at a level of up to 30% without any adverse effects. Crickets are deficient in amino acids methionine and arginine and their addition in the diets containing crickets is expected to further enhance the nutritional value of these feed resources. In quail (*Cotornix japonica*) 50% of fishmeal could be replaced by grasshopper meal without affecting growth or fecundity.

Evaluation of grasshopper meal and crickets containing diets in pigs is limited and to our knowledge does not exist in ruminants. In various fish species (African catfish, walking fish and Nile tilapia) the studies suggest that 25% of fishmeal can be replaced with grasshopper meal without any adverse effects.

Reports suggest that silkworm proteins have low rumen degradability and hence they could be a good feed resource for high yielding ruminant livestock. However a report suggests low intestinal protein digestibility of the ruminal undegradable fraction, while another report suggests higher digestibility of silkworm protein than groundnut cake proteins. More studies are required to evaluate the potential of silkworm proteins in the diets of, for example, high milk producing animals which respond to rumen bypass protein. In fattening diets of Jersey calves defatted silkworm meal can replace 33% of groundnut cake without affecting performance. In lambs and sheep as well the nutrient utilization results were encouraging. Also from experiments in growing and finishing pigs it can be concluded that defatted silkworm meal can replace 100% of soymeal or fishmeal. For common carp, full replacement of fishmeal with silkworm meal is possible. In comparison with plant protein sources (e.g. alfalfa or mulberry leaf meals) the silkworm meal is a better protein source for common carp. In fish species, silkworm meal has high protein digestibility (*ca* 85%). In silver barb fingerlings and Asian stinging catfish, 38% and 75% respectively of dietary protein can be replaced with silkworm protein without affecting the growth. For broilers, replacement of 50% fishmeal in the diets with silkworm meal is suggested. Limited studies on laying hens suggest that silkworm meal could be incorporated at 6% in the diets without any adverse effects. Caution is required in using silkworm meal in the diets of breeder males since detrimental effects on their breeding performance have been recorded. However, further studies on the evaluation of silkworm meal in laying hens and breeder males are required.

8. Future research areas

1. For insect meals to be a significant part of the animal diets produced by the feed industry, these need to be produced and processed in large amounts and preferably must be available throughout the year. Currently, insect rearing is done at a small scale. There is a need for establishing, cost-effective well-optimized mass insect rearing facilities that use well defined substrates, producing insects or insect meals of a defined quality.
2. For obtaining safe insect meals for use as feed, setting up of sanitation procedures for safe use of bio-wastes and managing diseases, heavy metals and pesticides needs to be considered.
3. There is a need to develop a regulatory framework and legislations for use of insect meals as animal feed, and to improve risk assessment methodologies.
4. More studies on evaluation of insect meals, processed insects or insect meals and insect proteins as livestock and aqua feed are required. These should be complemented with economic analysis.
5. Impact of feeding insect meals on product safety and quality from human health point of view, and studies on human acceptance of animal products obtained on feeding insect meals should be conducted.
6. Life cycle based studies on the environmental impact of using insects as animal feed vis-à-vis other protein rich animal feed resources, for example fishmeal, soymeal and other oilseed meals should be conducted.
7. Some insects (e.g. black soldier fly larvae, housefly maggot meal, mealworm, silkworm) are good in accumulating lipids/oils. Use of these oils for biofuel production and use of the defatted meal

as animal feed would enhance the economic returns from the insect mass rearing establishments. Also some insects are rich in chitin, which could also have many attractive uses.

8. Sound data must be generated on feed conversion efficiency of various insects and use of water and substrate per unit of insect biomass and insect protein production, to make informed decisions on the environmental impacts of using insects or insect meals vis-à-vis other conventional feed resources.

9. Insects could also be a source of high value bioactive compounds, which should be researched. Presence of substances with immunostimulatory effects on other animals (Ido et al., 2014; Miura et al., 2014) and anti-microbial peptides (Elhag et al., 2014) have been reported recently.

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