Recent advances in role of insects as alternative protein source in poultry nutrition

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ABSTRACT
Insects are considered as a potential substitute for fishmeal (FM) and soybean meal (SBM) in feeding mixtures for poultry diets. The intent of this paper is to appraise the current work relating to the use of insects as alternative protein in poultry feeding and the potential of large production of insects for the poultry feed industry. Certainly insects have a mammoth prospective as a protein source and other active substances (i.e. polyunsaturated fatty acids, antimicrobial peptides) for poultry. On the basis of numerous studies, insects meal belonging to the orders Diptera (black soldier fly, housefly), Coleoptera (mealworms), Megadrilacea (earthworm), Lepidoptera (silkworm and cirina forda) and Orthoptera (grasshoppers, locust and crickets), may be fruitfully used as feed ingredient in poultry diets. Information regarding their nutritional composition and biological evaluation was collected and compared it to SBM and FM.

1. Introduction
The consumption of insects (also called entomaphagy) is traditionally practised by more than two billion people worldwide, around 524 insect species are estimated to be consumed in Africa, 349 in Asia, 679 in the America, 152 in Australia and only 41 in Europe (Jongema 2015). Mexico has the highest number of insect species that are documented as edible, followed by Thailand, Congo, India, Australia, China and Zambia (Ramos-Elorduy et al. 2012; Jongema 2015). Insects constitute about three-fourths of the total organisms present on earth (Pedigo 2002). According to Rumpold and Oliver (2013), the insects could be divided into orders such as Diptera (black soldier fly, housefly), Coleoptera (mealworms), Megadrilacea (earthworm), Lepidoptera (silkworm and cirina forda) and Orthoptera (grasshoppers, locust and crickets). Out of the more than 2000 eaten species explained in scientific literature, beetles are 31%; caterpillars of butterflies and moths are 18%; bees, wasps and ants are 14% and locusts, grasshoppers and crickets are 13% (van Huis et al. 2015). Generally, insects are satisfactory sources of nutrients (proteins, fat, energy, vitamins and minerals). In this regard, literature showed that intake of 100 g of caterpillars’ fulfils about 76% of the requisite quantity of proteins on daily basis and accomplishes about 100% daily requirement of the vitamins in humans (Agbidye et al. 2009). Similarly, the nutritive values of three silkworm pupae are considered at par in nutrients of one chicken egg (Mitsuhashi 2010).

In poultry nutrition the supply of essential amino acids (EAAs) to grow rapidly in a short period of time is a key factor. For this reason SBM-based diets (as the major protein source of the diet) are supplied together with FM that covers any amino acid (AA) deficiency from vegetable proteins (Agazzi et al. 2016). The production of soybean is connected with deforestation, soil erosion, eutrophication, extensive use of pesticides, loss of biodiversity and a huge CO₂ footprint (van Huis 2015). Likewise, in recent years, the increasing price of soybean has become a critical aspect for the economic sustainability of the poultry meat industry, particularly in some developing countries (Gale and Arnade 2015). The FM is based on fish cultivated in aquaculture or marine fish species. Due to problems with over-fishing and environmental pollution, marine fish can be regarded as a limited resource. This is reflected by a drastic increase of the market price for FM during the last ten years, which has given rise to the demand for a new and more sustainable protein source (Veldkamp and Bosch 2015). Alternative protein sources of comparable value are therefore urgently needed in order to make poultry production a sustainable production form in the future. Moreover, the International Feed Industry Federation (IFIF 2016) predicts that livestock production will have doubled by 2050. Therefore, to meet the future requirements for protein new protein sources may be explored.

Insects are suggested as an alternative protein source in poultry feed, due to similar fat (30–40% dry matter; DM) and protein content (40–60% DM) to that of SBM or FM (Makkar et al. 2014). A shift from conventional protein sources such as SBM and FM towards insect meals might result in a more efficient use of natural resources and lower emissions of greenhouse gases as well as limiting eutrophication of water environments (loss of nutrients) (van Zanten et al. 2014). Due to the reasons mentioned above, the potential of insect protein in poultry diets has attracted much attention. Chickens with access to outdoor areas pick up insects at all life stages and eat them voluntarily, which indicates that they are evolutionarily adapted to insects as a natural part of their diet (Bovera et al. 2015a). Therefore, it seems reasonable to consider the inclusion of insect proteins as raw material to be used in...
commercial feed manufacturing and to develop intensive farming systems for insects. The FAO strongly recommends the use of insects as human food and animal feed as a tool for poverty alleviation (FAO 2010).

Another concern in Europe is the lack of protein-rich ingredients for animal feeding, especially to organic poultry due to exclusion of synthetic amino acids (AAs) and oil cakes extracted with solvents (SBM and rapeseed meal (EC, No. 834/2007). Current legislation allows 5.0% non-organic substrates in organic diets, until 31 December 2017 (EC 834/2007 No. 2092/91; EC 836/2014 No. 834/2007). It is a general concern that a 100% organic diet is unable to meet the requirements of EAAs of poultry, particular sulfur-containing AAs (Sundrum and Richter 2005). Furthermore, extensive use of dietary protein, for reaching the required amount of EAAs, is a common practise in organic poultry production (Elwinger et al. 2008).

Generally available literature confirms the feasibility of total or partial replacement of FM with insect meal. In particular, no negative effects have been reported on growth of insect meal-fed chicks, however most of papers have described similar or even better growth rates in chicks when compared to SBM or SBM + FM. In the same way the digestibility of nutrients seems to be unaffected, or at least improved, by the use of insect meal in poultry diet when compared with FM: this is especially true when insect meal has a comparable AAs profile and replaces the whole FM in the diet (Khatun et al. 2003, 2005) determining some economical positive effects (Okah and Onwujiariri 2012).

Until now, the main research efforts in poultry diets have focused on the black soldier fly (BSF), housefly (HF), mealworm (MW), silkworm pupae (SWP), earthworm (EW), grasshopper (Gr), locust, cricket and cirina forda (westwood). This review aims to explain the nutritional value and functional properties of the above mentioned insect species on the performance of poultry when these insects were used as a feed ingredient.

2. Black soldier fly larvae (Hermetia illucens)

BSF larvae are naturally found in poultry, pig and cattle manure but can also be grown on organic wastes such as coffee bean pulp, vegetables, catsup, carrión, and fish offal. It has been suggested that the larvae contain natural antibiotics (Newton et al. 2008). The BSF larvae (also called as BSF larvae meal, BSF prepupae meal and BSF maggot meal) are used live, chopped, or dried and ground forms.

2.1. Chemical composition

The DM content of fresh larvae is quite high (35–45%), which makes them easier and less costly to dehydrate than other fresh byproducts (Newton et al. 2008). Proximate analysis of BSF larvae contained 41.1–43.6% crude protein (CP), 15.0–34.8% ether extract (EE), 7.0% crude fibre (CF), 14.6–28.4% ash and 5278.49 kcal/kg gross energy (GE) on DM basis (Arango Gutierrez et al. 2004; St-Hilaire et al. 2007). Arango Gutierrez et al. (2004) reported that larvae are rich in calcium (Ca; 5–8% DM) and phosphorus (P; 0.6–1.5% DM), however, other minerals profile is potassium (K; 0.69% DM), sodium (Na; 0.13% DM), magnesium (Mg; 0.39% DM), iron (Fe; 0.14% DM), manganese (Mn; 246 mg/kg DM), zinc (Zn; 108 mg/kg DM) and copper (Cu; 6.0 mg/kg DM). Cullere et al. (2016) reported that the most abundant EAAs were valine (val) and leucine (leu), whereas alanine (alan) and glutamic acid (glu) were rich in defatted BSF larvae meal. The AAs concentration of defatted BSF larvae meal differed from the full-fat BSF larvae meal presented by De Marco et al. (2015): regarding EAAs, lysine (lys), methionine (meth), arginine (arg) and histidine (hist) contents were lower in defatted BSF larvae meal compared with those of the above-mentioned study, whereas for isoleucine (isoleu), leu, phenylalanine (phy), threonine (thr) and val the situation was reversed. The fatty acid (FA) composition of the BSF larvae depends on the FA 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 FA, while these proportions were respectively 43%, 11%, 12% and 3% for larvae fed 50% fish offal and 50% cow manure (Makkar et al. 2014). Total lipid content also increased from 21% to 30% DM. Feeding BSF larvae reared on cow manure and 22% of fish offal within 24 h of their puffsation was sufficient for a substantial enrichment in polyunsaturated fatty acid (PUFA), especially in docosahexaenoic acid and eicosapentaenoic acid (St-Hilaire et al. 2007). Recently, Maurer et al. (2016) reported that dried full-fat BSF larvae meal contained 41.5% CP, 26.5% EE, 4.3% ash, 0.80% Ca, 0.50% P, 0.08% Na and 0.33% chloride while dried partly-defatted BSF larvae meal consisted 59.0% CP, 11.0% EE, 5.0% ash, 0.98% Ca, 0.63% P, 0.08% Na and 0.28% chloride. In this study, the Ca content of the BSF larvae meal was very low (0.80 and 0.98%) compared to 5–8% mentioned by Arango Gutierrez et al. (2004). This might be due to harvest before the pre-pupal stage.

2.2. Effect of black soldier fly on poultry performance

BSF are possibly the most widely studied and the earliest referenced paper for their use as protein source in poultry feed (Hale 1973). They avoid human contact and are not generally considered a pest or pathogen vectoring species. Oluokun (2000) compared BSF larvae with SBM and FM on broiler production. The nutritional profile of maggots is comparable to FM and, in some aspects, better than SBM. The author suggested that maggot meal could replace FM to upgrade the nutritive value of SBM in the broiler diets without any adverse effect on the body weight gain (BWG), feed intake (FI) and feed conversion ratio (FCR). The feeding of dried BSF larvae as a substitute for SBM resulted in a similar BWG but a lower FI as compared to control indicating an improved FCR (Makkar et al. 2014). Recently, Maurer et al. (2016) carried out a feeding trial with partly defatted meal of dried BSF larvae in small groups of laying hens. Experimental diets contained 12 and 24% meal replacing 50 or 100% of soybean cake used in the control diet, respectively. After three weeks (wks) of experiment, there were no significant differences between feeding groups with regard to egg production, FI, egg weight and feed efficiency. There was a tendency (P = 0.06) for lower albumen weight in the 24% meal group; yolk and shell weights did not differ. No mortality and no sign of health disorders occurred. The DM of faeces increased with increasing proportions of
meal in the diet, with a significant difference between 24% meal and the control groups ($P = 0.03$). An increase of black faecal pads was observed in the 12% and 24% meal groups. Higher DM of faeces and a larger proportion of dark, firm faecal pads with 24% gave reason to assume that in this diet the proportion of meal was too high. The causes of these differences are not fully understood. In growing broiler quail, Cullere et al. (2016) tested three diets as control, 10% defatted BSF larvae meal (substituted 28.4% soybean oil and 16.1% SBM) and 15% defatted BSF larvae meal (substituted 100% soybean oil and 24.8% SBM). It was observed that quails showed the same BWG, FI, FCR and mortality rate in all dietary groups. Apparent digestibility of nutrients (DM, OM, CP, EE and starch) was overall comparable among the three groups except EE, whose digestibility was the highest ($P < .001$) in control (92.9%) and 15% BSF meal (89.6%) groups. Feed choice trial showed that broiler quails did not express a preference toward control or 15% BSF meal diets and breast meat weight and yield did not differ among all groups.

It may be concluded that maggot meal could replace FM or SBM in the broiler and laying hen diets without any adverse effect on performance.

3. Housefly (Musca domestica)

Common HF larvae can grow on poultry, pig and cattle manure; they have yet been reared on municipal organic waste. Maggots are HF larvae that are prepared to make maggot meal. They have a rapid reproductive rate, high feeding value and easy to process and stored for sustainable use. Maggots are available throughout the year (Moreki et al. 2012).

3.1. Chemical composition

The HF maggots are rich in CP (63.99%) and EE (24.31%) as reported by Hwangbo et al. (2009). The CP and EE contents are changed with the drying method and age of the maggots; CP contents decreased and EE content increased with age (Aniebo and Owen 2010). Pretorius (2011) found that HF larvae meal (on DM basis) contained 60.38% CP, 14.08% EE, 10.68% ash and GE value of 4800.80 kcal/kg and the HF pupae contained 76.23% CP, 14.39% EE, 7.73% ash and GE value of 4877.23 kcal/kg. He noted that the HF larvae and pupae meal had an apparent metabolizable energy (AME) value of 3398.77 kcal/kg and 3618.51 kcal/kg, respectively. The maggots showed higher Ca, P and metabolizable energy (ME) content (4140 kcal/kg) than SBM (2250 kcal/kg). The essential fatty acid (EFA), linoleic acid, was found at levels of 26.25 and 36.27% of the total fats for the HF larvae and pupae meal, respectively (Pretorius 2011). He also reported that the maggots contained higher percentage of palmitoleic acid, oleic acid and linoleic acid as EFAs than the HF pupae. The maggots had also higher AA content than the SBM and contained a higher percentage of EAAs (29.46%) than non-EAAs (28.22%). Specifically, the maggots contained higher quantity of the EAAs lys, arg, phyr and val. Maggots have low levels of meth and cys, it would be necessary to provide meth along with feed that contains maggots (Pretorius 2011). Bosch et al. (2014) reported that phyr, lys and Meth contents of CP were found the highest in HF pupae as compared to the lesser MW. With regard to protein quality, maggots are comparable to meat and bone meal as well as FM and are superior to SBM (NRC 1994; Inaoka et al. 1999). The maggots had great apparent digestibilities for protein (98.50%) and EAAs (94.80%) more than the SBM. Ukanwoko and Olalekan (2015) assessed the effect of source and the time of harvest on proximate composition of maggot meal. It was noted that maggot meal with raw egg attractant had the highest CP (45.84%) and EE (19.30%) as compared to maggot meal without fly attractant (39.58 and 19.12%, respectively). Maggot meal with chopped mango attractant had the highest ash content (7.13%). Maggot meal with raw egg attractant had the highest CF (6.14%). The highest value of CP was observed after 48 h of harvest (58.06%). The highest EE and CF were observed at 120 h of harvest (24.60 and 7.60%, respectively).

3.2. Effect on digestibility

Apparent fecal digestibility of dried HF meal was evaluated in broiler chickens in two studies. Hwangbo et al. (2009) fed 4-wk-old broilers a diet with 30% dried HF larvae meal or SBM for 7 d and Pretorius (2011) fed 3-wk-old broilers a corn meal-based diet containing 50% dried HF larvae meal or dried HF pupae meal. The results showed that the value of apparent fecal digestibility of CP for HF larvae in first study was higher (98.5%) than the second study (69%). The latter study also showed that CP fecal digestibility was greater for HF pupae than for the larvae. Digestibility of most AAs was in both studies around 90% or greater. Surprisingly, Pretorius (2011) reported considerably greater apparent fecal digestibility values for individual AAs than for CP. There is a need for evaluation of nutrient digestibility of (processed) insects as feed ingredients, which is a prerequisite for formulating insect-containing feeds. Bosch et al. (2014) reported in vitro digestibilities of organic matter and nitrogen in HF fly pupae were found as 83.2 and 84.3%, respectively. Pieterse and Pretorius (2013) evaluated the dried larvae and pupae meal using chemical- and broiler-based biological assays. Proximate analysis showed as CP (60.38 and 76.23%, with total tract digestibility (TTD) of 69% and 79%, respectively), EE (14.08 and 14.39%, with TTDs of 94% and 98%, respectively), CF (8.59% and 15.71%, with TTDs of 62% and 58%, respectively), GE value (4800.80 kcal/kg and 4877.23 kcal/kg, respectively) and apparent ME value (3398.77 kcal/kg and 3618.51 kcal/kg, respectively) in the pupae meal with raw egg attractant (39.58 and 19.12%, respectively). Maggot meal with chopped mango attractant had the highest ash content (7.13%). Maggot meal with raw egg attractant had the highest CF (6.14%). The highest value of CP was observed after 48 h of harvest (58.06%). The highest EE and CF were observed at 120 h of harvest (24.60 and 7.60%, respectively).

3.3. Effect of house fly on poultry performance

There is an extensive literature on the suitability of maggots or pupae of HF to rear broilers chicks (Åkpodiete and Inoni 2000; Téguia et al. 2002; Awoniyi et al. 2003; Adeniji 2007; Adesina et al. 2011; Okah and Onwujiariri 2012), layers (Dankwa et al. 2002; Agunbiade et al. 2007) and ducklings (Mensah et al. 2007). In all cases, these studies showed that maggots, either fresh or dried, could entirely or partially replace conventional
protein ingredients such as FM, meat meal or groundnut cake without affecting survival, daily FI, BWG, FCR, egg laying and other performance factors. Téguya et al. (2002) obtained better results with maggot meal as compared to conventional FM (Téguya et al. 2002). However, when various proportions of maggot and FM, or maggot and meat meals were used, the best growth performance was often observed with variable combinations of maggot meal and conventional meal than that of single protein source. This may be due to the combination of maggot meal with conventional feed might provide a more balanced diet for the birds. Most trials indicated that partial replacement of FM by maggot meal in broiler diets is possible. The HF maggots and pupae can replace 7% of the FM in broiler chicken feed (Iinoaka et al. 1999). Inclusion rates greater than 10% in the diet decreased FI and performance, perhaps due to the darker colour of the meal, which may be less appealing to chickens (Atteh and Ologbenla 1993; Bangboso 1999). An imbalanced AAs profile may also explain the negative effects observed when the inclusion levels are greater than 10% (Makkar et al. 2014); meth supplementation might enhance performance. Hwangbo et al. (2009) supplemented broiler feed with 10–15% HF larvae and found improvement in growing performance and carcass quality. The CP contents remained steady in the breast muscle but lys and trypt contents increased. This may be due to the best AAs profile, rich CP content (63.99% DM) and high protein digestibility (98.5%) of the larvae. Awoyi et al. (2003) conducted a performance trial with 3- to 9-wk-old broiler chickens that were fed five isonitrogenous and isocaloric diets in which maggot meal replaced 0, 25, 50, 75 and 100% of 4% FM in the diet. The diet with 25% of FM protein replaced with maggot meal was the most efficient in terms of average weekly BWG and protein efficiency ratio. At 9 wk of age, however, live, dressed and eviscerated weights as well as relative length, breadth, and weights of the pectoral and gastrocnemius muscles were not significantly influenced by the diets (Awoyi et al. 2003). Atteh and Ologbenla (1993) found that a 33% replacement of conventional FM by maggot meal was an ideal for chicks, but higher proportions of maggots reduced FI and BWG. Pretorius (2011) conducted a performance study with broilers using seven dietary treatments consisting of a commercial diet (com-soybean) and diets supplemented with 10% HF larvae meal, 10% FM, 25% HF larvae meal, 25% FM, 50% HF larvae meal and 50% FM. No significant differences in performance results were observed between a 10% HF larvae meal and a 10% FM supplementation. Broilers fed the 10% larvae meal or 10% FM diets had significantly greater breast muscle portions relative to carcass weight than the chicks that received the commercial diet. The 25% HF larvae meal supplementation significantly improved broiler BW, FI and cumulative FI when compared with the 25% FM supplementation diet in the growth phases. Okah and Onwujiariri (2012) also reported that the chickens fed the control diet gained lower BW than those fed the 20 and 30% of maggot meal in replacement of FM.

There is little published literature on the use of HF larvae meal in the diets of laying hens and the only published literature of interest was the work done by Agunbiade et al. (2007), who investigated the effect when FM was replaced with larvae meal in the diets of laying hens. In the study, FM was replaced with larvae meal in a cassava based diet in two laying hen hybrids (50 wks in lay). The results showed that FI and FCR were not affected by the experimental treatments ($P > .05$), but the hen-day production was significantly affected ($P < .05$) when 3.00% FM and 4.72% larvae meal were fed. This effect can be due to the complimentary effect when larvae and FM are supplemented together which creates a better AAs profile supplied to the animal (Agunbiade et al. 2007). Larvae meal supplementation had no significant effect ($P > .05$) on egg quality traits when compared to the control diet (Agunbiade et al. 2007). The findings showed that when larvae meal were supplemented at a level of 7.08% together with 1.50% FM and at a level of 9.44% with no FM a significant decrease ($P < .05$) in shell thickness and shell weight were observed. These differences are related to the lower Ca content associated with larvae meal supplementation and not an inherent negative effect of larvae meal. Larvae meal could replace 50% of the dietary animal protein supplied by FM without deleterious effects on egg production and shell strength. In another study, supplementation of maggots (30–50 g) also improved ($P < .05$) clutch size (115 vs 9.5), number of eggs hatched (9.8 vs 7.1), egg weight (43.5 vs 33.6 g) and chick weight (34.2 vs 29.8 g) as compared to only scavenging in the village chicken (Dankwa et al. 2002). Based on the results of above studies; it seems that maggot meal could be replacement for FM in broilers and laying hens feeding.

4. Mealworm larvae (Tenebrio molitor)

Only a limited number of organic waste sources have been described in literature for rearing of yellow MW. The MW has been grown on dried and cooked waste materials from fruits, vegetables, and cereals in various combinations (Ramos-Elorduy et al. 2002). They are omnivores but are typically fed on wheat bran or flour supplemented with soybean flour, skimmed milk powder or yeast (Makkar et al. 2014).

4.1. Chemical composition

Scientific literature regarding the nutritive composition of MW larvae shows variation depending on diet, climate conditions and phase of development. The minimum and maximum values of CP, EE, ash, CF and energy in MW larvae were reported as 45–60% (Józefiak and Engberg 2015), 25–43% (van Broekhoven et al. 2015; Józefiak and Engberg 2015), 3.0–4.5% (Ramos-Elorduy et al. 2002; Józefiak and Engberg 2015), 5.0–8.8% (Ramos-Elorduy et al. 2002; Józefiak and Engberg 2015) and 244–781 cal/kg DM, respectively (Finke 2002; De Marco et al. 2015). The total CP content of MW adult, exuvium and excreta were reported as 63.34, 32.87, and 18.51%, respectively (Ravza-naadi et al. 2012). Same researchers reported that total EE content was 7.59, 3.59 and 1.3% for MW adult, exuvium and excreta, respectively. Recently, Bovera et al. (2015b) compared the chemical composition and AAs profile of MW larvae with SBM and reported that CP, EE and acid detergent fibre (ADF) contents were higher in MW larvae (51.93, 21.57 and 7.20%, respectively) than SBM (44.51, 1.84 and 4.79%, respectively). The two protein sources had a different composition in EAAs,
and this was particularly manifest for meth+cys (the SBM showed contents 3.27 times higher than MW) but also for isoleu (+1.75), arg (+1.70) and lys (+1.68). Moreover, thr (+1.26), leu (+1.25), hist (+1.19) and val (+1.10) were higher in SBM, whereas the tryp content was higher in MW larvae than in SBM. They concluded that only meth and lys content of both protein sources were not adequate for broilers and a diet supplement was necessary. All the other AAs had a sufficient concentration to satisfy broiler needs for growth also in MW larvae. Recently, Hussain et al. (2017) recorded a considerable amount of CP (45.83%) and EE (34.20%) and almost all EAAs especially meth (1.34%) and lys (4.51%) in MW.

Ravzanaadii et al. (2012) reported that MW larvae are too low in Ca (434.59 mg/kg) and rich in K (9479.73 mg/kg) and P (7060.70 mg/kg). The Ca content and the Ca:P ratio are not adequate for poultry production (particularly for hens), but such problems can be solved by feeding MW with a Ca fortified diet for 1 or 2 d (Makkar et al. 2014). The micro-minerals profile was found as Zn (104.28 mg/kg), Fe (66.87 mg/kg) and Cu (13.27 mg/kg). Remarkable composition of the long chain of FAs in larvae meal were detected with the highest component oleic acid alongwith linoleic acid and palmitic acid as values 43.17, 30.23, 16.72%, respectively (Ravzanaadii et al. 2012). Finke (2015) reported that MW contained considerable quantities of most of the B vitamins (B2: 8.7; B3: 46.5; B5: 15.6; B6: 6.90; folic acid: 1.55 & biotin: 0.43 mg/kg) and choline (1410 mg/kg), although lower levels of both vitamins B1 (1.1 mg/kg) and B12 (0.0013 mg/kg) were found in MW.

4.2. Effect on digestibility

Bosch et al. (2014) reported that in vitro organic matter and nitrogen digestibilities of yellow MW were found as 91.5 and 91.3%, respectively. De Marco et al. (2015) compared two insect larval meals (MW and BSF) regarding the apparent digestibility coefficients of the total tract (CTTAD) of nutrients and the AME and AMEn and amino acid apparent ileal digestibility coefficients (AIDC) for broilers. There was non-significant difference between two insect meals for the CTTAD of the all nutrients except EE value in MW showed more digestible (0.99) than that of BSF meal (0.88). Similarly, no statistical difference was noted between two insect meals for AME and AMEn (AME = 4026.94 and 4151.14 kcal/kg DM for MW and BSF, respectively; AMEn = 3826.31 and 3964.84 kcal/kg DM for MW and BSF, respectively). The average AIDC of the AAs was found higher in MW (0.86) as compared to BSF (0.68). Above study provided updated information and never before evaluated nutritional values of MW and BSF meal, which could be two potential future ingredients for use in the formulation of broiler diets. The acquired knowledge of AME and AMEn will be useful for nutritionists and feed companies to obtain better formulate novel poultry feeds.

4.3. Effect of mealworm on poultry performance

Hussain et al. (2017) reported that BWG was improved with increasing level of MW (1322.0, 1346.3 and 1423.3 g for 0.1, 0.2 and 0.3% MW, respectively). Mean FCR for supplemented groups (1.88, 1.84 & 1.75 for 0.1, 0.2 and 0.3% MW, respectively) was better (P < .05) as compared to control group (2.01). No significant difference was seen in the FI of different groups. The dressing percentage was higher (P < .05) at 0.3% MW supplemented group (66.10) as compared to control (63.28). It was observed that organolyptic properties evaluation i.e. taste, tenderness, juiciness, flavour and colour were not influenced by the addition of MW in the diet of broilers. Antibody titer against Newcastle disease virus for all experimental groups showed non-significant result. This indicated that MW supplementation had no adverse effects on heamagglutination antibody titer. Gross return and net profit was higher (P < .05) for 0.3% MW group (0.41US$) followed by 0.1% MW (0.40US $), 0.2% MW (0.36US$) groups and lowest return (0.34 US$) was control group.

Ramos-Elorduy et al. (2002) reduced the level of inclusion of SBM (55%CP) to 31, 26 and 20% of the diet and replaced it by 0, 5, and 10% of dried yellow MW, respectively. Sorghum (9% CP) represented 61–64% of the diet (by weight) and did not differ among the three treatments. Performance results after 15 d showed no significant differences among treatments. Fresh MW larvae contained 40% DM and 1.0–4.5% total ash (Józefiak et al. 2016). The above stated results are main causes for limiting their supplement (up to 10% of DM of total diet) in the broiler diets.

Ramos-Elorduy et al. (2002) reported that MW may be added in SBM based diets without any negative effects on BWG, FI and FCR. Likewise, Schiavone et al. (2014) noticed better BWG at maximum level of 25% MW. Bovera et al. (2015a) replaced completely SBM with MW larvae in broiler’s diet. The use of MW as the main protein source in the broiler diet had no significant effect on most growth performance, carcass traits and chemical & physical properties of meat. However, the FCR in the entire experimental period (30–62 d) was improved (P < .05) in the MW group compared with the SBM group. The full digestive system in broilers fed SBM had a lower (P < .05) absolute and relative weight than that of broilers fed MW larvae. Similarly, the weight and the percentage of the spleen in the SBM group were lower (P < .05) than those in the MW larvae group. The length of the entire intestine in the group fed larvae meal was greater (P < .05) than the other group and the same happened when intestinal length was expressed as percentage of broiler BW (P < .05). Among the different intestinal tracts, the ileum and ceca of broilers fed larvae meal had a greater (P < .05) length than that of broilers fed SBM. In another study, Bovera et al. (2015b) reported that MW larvae did not affect FI and BGR of broilers from 30–62 d of age when compared to an isoproteic and isoenergetic SBM diet. However, the FCR was more favourable in the MW larvae group (3.62) than SBM group (4.13) from 46 d of age and in the entire period of the trial and the European efficiency factor was also higher in broilers fed on the larvae diet (156.2) than SBM diet (132.6). The protein efficiency ratio was higher in the SBM (1.92) than in the insect meal group (1.37). The albumin/globulin ratio was decreased when broilers fed on insect meal diet. Such low albumin/globulin ratios indicated better disease resistance and immune response of birds, probably due to the prebiotic effects of chitin (a polysaccharide constituting insects and crustaceans exoskeleton). The increase of aspartate aminotransferase in broilers of the insect meal group falls in the...
normal range for broilers and is not accompanied by an increase in gamma glutamyl transferase, lactic dehydrogenase or lactic dehydrogenase, thus suggesting no alteration occurred in liver and muscle cells.

The results showed that MW larvae can be a suitable alternative protein source for broilers and also when used as principal protein contributor to the diet.

5. Earthworm

The EW belongs to the phylum Annelida (ringworm). They are generally classified into three ecological categories regarding their feeding strategy: endogeic (soil feeders), anecic (burrowers) and epigeic (litter feeders). Species from the first two categories feed on a blend of organic matter and soil while epigeic EW feed exclusively on organic matter (Dominguez et al. 2010).

5.1. Chemical composition

Babiker (2012) recorded rich source of ash contents in EW (43.50%), whereas CP, CF, EE, NFE and ME were found as 38.87, 1.15, 3.71, 9.81% and 7.99 MJ/kg, respectively on DM basis. Mineral profile was noted as Ca (0.93%), P (0.50%), K (0.58%), Mg (0.36%), Cu (109.86 mg/kg), Fe (5.69 mg/kg), Mn (268.73 mg/kg) and Zn (151.17 mg/kg). The EW had the considerable amount of lys contents (2.56%). Sogbesan and (268.73 mg/kg) and Zn (151.17 mg/kg). The EW had the considerable amount of lys contents (2.56%). Sogbesan and Ugwumba (2008) reported that the proximate and mineral composition (on DM basis) of EW contained 63.0% CP, 5.9% EE, 1.9% CF, 8.9% ash, 11.8% NFE, 0.53% Ca, 0.62% K, 0.94% P and 3525.36 kcal/kg ME. In addition, the same authors found that the EAAs composition (g/16 gN) for the EW they analyzed as arg (2.83%), hist (1.47%), isoleu (2.04%), leu (4.11%), lys (6.35%), meth (5.30%), phy (6.26%), thr (4.43%) and val (4.43%).

Istiqomah et al. (2009) reported that proximate analysis of earthworm meal on DM basis (EWM; Powdering method of EW was done by using 3% formic acid addition) was found as 63.06% CP, 7.8% CF, 18% EE, 0.19% CF, 12.41% NFE and 5.81% ash. EWM was 4.44% and 1.2%, respectively. In another study, EWM (DM basis) contained 52% CP, 7.8% CF, 18% EE and 12.65% ash (Mohanta et al. 2016).

5.2. Effect of earthworm on poultry performance

The EW are a natural feed source for poultry kept under free-range systems and, live or dried, are highly palatable to poultry (Tiroesele and Moreki 2012). Loh et al. (2009) replaced partially SBM and FM with EW in broiler diets (0, 5, 10, 15 and 20%). The BWG and FCR of the 10% (2089 g and 1.99, respectively) and 15% (2087 g and 1.94, respectively) EW groups were better (P < 0.05) than that of the control group (1928 g and 2.08) but no effect on FI. The digestibility of CP for EW was 63%. In Japanese quail diets, Prayogi (2011), who replaced FM with EWM as 0, 5, 10 and 15%. Feed consumption was reduced (P < 0.05) in birds fed EW diets (9.53, 9.83 and 9.14 g/d for 5, 10 and 15% EW) than that of birds fed control diet (11.53 g/d). However, the BWG of the birds fed 10% EW (3.67 g) was better (P < 0.05) than those of the birds fed 5% (3.59 g/d) and 15% (3.0 g/d) EW diets. Son and Jo (2013) reported that adding 0.4% EWM to the broiler diets improved the FI and BW and also increased the digestibility of the nutrients. Bahadori et al. (2015) evaluated the effect of five dietary treatments on broiler performance such as control, diet containing 1% vermihumus without EW, diet containing 1% EW and 1% vermihumus, diet containing 2% EW and 1% vermihumus and diet containing 3% EW and 1% vermihumus. The results showed that FI and FCR decreased (P < 0.05) in whole period with increasing the amount of EW. The effect of experimental treatments was not significant on BWG and some carcass component. Overall, the results showed that 2% and 3% of EW along with 1% vermihumus improved the FCR of broiler chickens.

6. Grasshoppers

The GH can be harvested from their habitats such croplands, grasslands, wetlands and paddocks (Khusro et al. 2012). Harvesting GH from these habitats could reduce the use of hazardous chemical to control pest. Thus these harmful insects harvesting GH from these habitats could reduce the use of hazardous chemical to control pest.

6.1. Chemical composition

The nutrient composition of grasshopper meal (GHM) was assessed by many scientists (Ojewola et al. 2003; Ojewola and
It is also important to know whether GH can compete with the other conventional protein sources like FM, SBM etc. Above description indicated that Acridids have been identified as one potential feed component for poultry feed since they have higher CP content than other protein sources such as SBM (48%) and FM (50–55%). Hasanuzzaman et al. (2010) and Adeniyi et al. (2011) reported EE content of fish and meat varied from 4 to 9% which is also similar to that of GH (Ganguly et al. 2013). According to Koumi et al. (2011), the carbohydrate content of fish and SBM could be around 23 and 27%, respectively, which are very close to the value of the carbohydrate content of almost 30% noted in the GH (Ganguly et al. 2013). Among vitamins, this insect has a higher proportion of thiamin (vitamin B1) than wheat germ, peas, bread, beans, rice, soybean, milk and egg; whereas for riboflavin (vitamin B2) it is richer than cheese, bread, beef liver, milk, eggs, yogurt, spinach, trout and chicken and niacin (vitamin B3) is in greater amount than bread, peas, beans, corn, wheat, milk, bacon and eggs, and in general is poor in terms of vitamin C (Ramos-Elorduy and Pino 2001). However, mineral contents in GH were quite lower as compared with meat, fish, soybean or corn (Adeniyi et al. 2011; Koumi et al. 2011).

It may be concluded that chemical composition of GH can be comparable with other protein sources used in poultry diets.

6.2. Effect of grasshopper on poultry performance

Liu and Lian (2003) replaced 20% and 40% FM with GHM in broiler diets without any effect on BWG and FI. However, Ojewola et al. (2003) reported depressed BWG and FE except protein content of carcass when added GHM at the levels of 2.5–7.5% in broiler diets (1–49d). Ojewola et al. (2005) suggested that 2.5% GHM in the broilers diet was appropriate and cheaper alternate against imported FM (100% replacement) whilst the generally diet contained somewhat less protein (22.2% vs. 22.8%).

When maize-GHM-SBM diets were formulated on an equal CP and TMEEn basis, up to 15.0% GHM could replace control diet without any adverse affects on broiler BWG, FI, gain:feed ratio from 8 to 20 days post-hatching (Wang et al. 2007). In two studies, Hassan et al. (2009) and Muftau and Olorude (2009) evaluated the effect of replacing FM with GHM (0, 50 and 100%) on the carcass characteristics and the economics of broiler chicken production. The BWG of birds increased significantly as the level of GHM increased. The FI of GHM was significantly lower than the control diet. The carcass measurements showed significant difference (P < 0.05) in the treatment means, with the exception of the breast, pancreas, proventriculus, heart, spleen, liver, lungs, crop and chest. Whole GHM diet showed the highest return (16.61 US$), followed by 50% GHM diet (12.23 US$) and 100% FM diet (6.69 US$). They suggested that GHM can completely replace 100% of FM in broiler’s diet, without affecting their biological performance and economic return. Japanese quails (Coturnix japonica Japonica) were fed with various diets in which GHM gradually replaced FM. For a range of growth parameters, the best results were obtained with the diet in which 50% of FM was replaced with GHM. Fecundity (i.e. the number of eggs

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laid per female) was significantly higher compared with the control treatment (Haldar 2012). Sanusi et al. (2013) replaced FM (by 25, 50, 75 and 100%) with GHM in broiler starter and finisher diets. The results showed that at the starter phase, daily FI (57.42–60.30 g), daily BWG (17.9–20.2 g) and FCR (2.9–3.4) among diets were statistically similar. Similarly, the corresponding values of daily FI (135.5–146.1 g), daily BWG (34.5–45.8 g) and FCR (3.2–4.5) at finisher phase were also statistically similar among the diets. The results suggested that GHM can completely replace FM in broiler diets without adverse effect on the performance characteristics.

In two studies, Sun et al. (2012, 2013) assessed the impact of a diet containing GH on the characteristics of lipid oxidation of carcass meat, physicochemical and sensory characteristics in a free-range, grassland-based broiler production system. A total of 80 (28d-old) male broilers were introduced into a rangeland where there was a dense population of GH (PB). Control birds (CB) were reared under intensive conditions and given a maize-soybean diet. The results showed that the activities of glutathione peroxidase (GSH-Px) and superoxide dismutase (SOD) in the muscle of chicken breasts or legs from PB broilers were higher (GSH-Px: 0.123 & 0.102 U/g; SOD: 70.13 & 65.24 U/g for breast and legs, respectively) than those from the CB (GSH-Px: 0.095 & 0.083 U/g; SOD: 58.53 & 50.96 U/g for breast and legs, respectively), but no significant differences were found for the activities of catalase between the PB broilers and the controls. Furthermore, treatment PB produced birds with significantly lower live BW, breast, wing, thigh and drum weights, and higher dressing percentage and breast percentage of carcass, compared with CB. Treatment PB produced breast meat with significantly higher redness values, shear force and protein content, and lower pH values, cooking loss, moisture and fat content compared with CB. Sensory panel results for breast and thigh meats showed no treatment effect on colour and juiciness, but significantly higher scores for chewiness, flavour, aroma and overall appreciation, and lower scores for tenderness from treatment PB compared with CB. They concluded that meat in free-range broilers feeding on GH has more antioxidative potential and longer storage life and rearing chickens on rangeland may provide an alternative way to produce poultry meat which is considered superior by modern consumers.

7. Locust (Schistocerca gregaria)

The common names are locust meal, locusts, desert locust, migratory locust, brown locust, red locust. Locusts and other Orthoptera used for poultry feeding are fed live (free-range chickens) or dried and ground (broilers). Sometimes they are boiled before drying (Khusro et al. 2012).

7.1. Chemical composition

Gibreil and Idris (1997) reported that locust meal contained higher CP (89 vs 45%) and ME (2714 vs 2000 kcal/kg) but lower EE (3.9 vs 4.8%), Ca (0.26 vs 10.6%) and P (0.44 vs 3.30%) contents than super-concentrate meal used in broiler diets. The AA profile of locust meal (%DM) contained arg (2.76), gly (3.5), hist (0.98), leu (3.39), isoleu (2.21), lys (1.97), phy (1.51), thr (1.81), tyr (3.11) and val (3.26). Data showed locust meal fail to excel or simulate the super-concentrate meal in terms of Ca, P and lys. In this study, the AA profile lacked information on sulphur-containing AAs. Adeyemo et al. (2008) reported that proximate analysis (DM basis) of desert locust meal was found as 52.3% CP, 12% EE, 19% CF and 10% ash. Variation in results of different studies could be attributed to differences in locust species, stage of their development and the season of the year during which the samples were collected.

7.2. Effect of locust on poultry performance

Limited number of studies was conducted on poultry performance. In the earlier study (Fronda 1935), replacement of FM with locust meal in broiler diets was not improved the performance except better palatability. However, the current studies showed partial substitution of FM with locust meal is usually suitable. Adeyemo et al. (2008) replaced 50% FM with desert locust meal (i.e. 1.7% in the diet) in broilers starter diets and found better BWG (2097.43 g), FI (4658.28 g) and FCR (2.22) as compared to higher levels of locust meals (3.4% and 6.8%) and control diets. Gibreil and Idris (1997) used locust sprayed with insecticides and non-sprayed in broiler diets and replaced equivalent amount of protein provided by 5% super-concentrate of control diet. Three experimental diets were fed to groups of commercial broiler chicks from 0 to 2 or 7 wks of age. The results indicated that locust meal sprayed with insecticide tended to depress FI (2.9 kg/bird) as compared to non-sprayed locust meal (3.04 kg/bird) and control (3.35 kg/bird) groups. Moreover, live BW and FCR were depressed by both types of locust meals than control group. Locust meal was deficient in lys and therefore cannot be used as sole protein supplement in sorghum based broiler diet and it can be used as a base for production of commercial protein supplements.

8. Crickets (Gryllus testaceus walker)

Common names are crickets, cricket meal, house cricket, field cricket or Mormon cricket and it inhabits paddy fields and fallow lands. It can survive and grow well on a variety of organic materials (Makkar et al. 2014) including forage diets, agricultural (rice bran, cassava tops or leaves) and food industry (spent grain and residues from mungbean sprout production) by-products and plants considered as weeds are potential cheap and sustainable feed sources. Crickets are considered easy to rear at farm (FAO 2013) and that is probably one important reason why there are very large numbers of cricket farmers (around 20,000) raise crickets in Thailand (FAO 2013).

8.1. Chemical composition

Crickets were reported to have a high CP level ranging from 55 to 73% and sufficient EAAs, except for meth and lys, which can be supplied directly in the feed (Finke 2002; Barroso et al. 2014). Wang et al. (2005) reported that the CP and EE of field cricket (DM basis) was 58.3% and 10.3%, respectively which is comparable with those of conventional protein feed supplements i.e. SBM (46.8 and 1.84%, respectively), meat meal (48.5 and 8.47%, respectively) and FM (60.2 and 4.11%, respectively).
The percentage of lys, meth and cys were 4.79, 1.93 and 1.01%, respectively in field cricket while they were 4.51, 1.59 and 0.49%, respectively in FM, indicated that the EAA contents of this insect were adequate for poultry (Wang et al. 2005). However, in studies on the Mormon cricket, CP contents were noted as 58% (DM basis) and AAs analyses indicated that meth, arg and tryp, in that order, were found as limiting amino acids (DeFoliart et al. 1982). The true amino acid digestibility (TAAD) coefficients for EAs of field cricket ranged from 82% for cys to 99% for asparagines (Wang et al. 2005). The average of TAAD coefficients of field cricket (92.9%) was higher than that of FM (91.3%). The TMEn of the field cricket was found as 2960 kcal/kg measured in conventional birds (Wang et al. 2005). Adeyeye and Awokunmi (2010) found CP for males (32.4%) and females (25.8%) of field cricket, while carbohydrate was 48.9 and 54.8% for females and males, respectively. The energy content of cricket meal ranged from 3582.69 kcal (male) to 3821.53 kcal (female) which compared favourably with the cereal value of 3104.99 kcal (male) to 3821.53 kcal/kg. Also, the Fe content is 31–100 mg/kg. Field cricket is a good source of Na (1037–2226 mg/kg), K (746–1112 mg/kg), P (10880–10936 mg/kg) and Zn (515–1032 mg/kg). Abdul Razak et al. (2012) compared the nutritive values of house cricket meal with given values of SBM and FM as reported by Mcdonald et al. (1995). The CP content of house cricket meal was 60.4% and this value was higher than that of SBM (44%) or FM (59.95%). Total amount of tryp, tyr and val in the house cricket meal were 2.8%, 2.4% and 3.2%, respectively. These values were higher than those in SBM (0.6, 1.4 and 2.4%, respectively) and FM (0.7, 1.8 and 3.0%, respectively). The percentages of lys, meth and cys in cricket meal were 2.4, 0.5 and 0.8%, respectively. These values were similar to those in SBM (2.9, 0.6 and 0.7%) but lower than FM (4.5, 1.7 and 0.8%). Total ME value (kcal/kg) for cricket meal (3114.24) was close to that of corn (3202.67) but was much higher than that of SBM (2165.39) and lower than FM (3585.09). Similarly, Bosch et al. (2014) reported that house crickets contained the most CP (70.6%) followed by lesser MW (64.8%) and the roaches (66.3%) and house crickets were relatively high in Arg (5.7%) but low in Hist (3.4%). Finke (2015) reported that vitamins E and K contents in cricket were 53.7 IU/kg and 78.4 mg/kg, respectively. This insect contained substantial quantities of most of the B-vitamins (B1; 2; B2; 16.6; B3; 29.5; B5; 20.3; B6; 2.13; folic acid; 1.07; biotin: 0.21 and B12; 0.193 mg/kg) and choline (1.02 mg/kg). Crickets contained sufficient vitamins B1 and B12 to meet the requirements of both rats and poultry. This insect also contained sufficient quantities of inositol (345 mg/kg). It revealed that the cricket contained not only high quantity of protein but also considerable amounts of digestible AA, carbohydrate, energy, vitamins and minerals for poultry.

### 8.2. Effect of cricket on poultry performance

In feeding trials, corn-and-cricket-based diets showed significantly better growth of broiler chicks than conventional corn-soybean-based diet supplemented with meth at 3 wks of age (DeFoliart et al. 1982). It was observed that supplementing the corn-cricket diet with additional AAs resulted in a non-significant increase in growth. In later experiment, Finke et al. (1985) fed purified diets to broiler chicks to identify the limiting AAs in Mormon crickets and found that meth and arg were probably colimiting. However, when Mormon crickets were incorporated into practical diets replacing SBM as the major source of protein in an 8-wk feeding trial, the corn-cricket diet compared favourably with a corn-SBM diet, with non-significant differences in chick BWG or feed:gain ratio. In taste tests, no off-flavour was detected in the meat of broilers that had been fed Mormon crickets. In another similar experiments, Nakagaki et al. (1987) conducted two broiler feeding trials to determine the protein quality of dried house cricket meal. In the first trial, semi-purified diets were used to identify limiting amino acids. There were no significant differences in BWG of chicks fed diets with amino acid additions, but feed:gain ratios showed that arg, meth and tryp were limiting. In the second trial, dried house cricket meal was included into practical diets replacing SBM as the major source of protein. There were no significant differences in BWG between chicks fed corn-soybean meal diet and those fed corn-cricket diets. However, feed:gain ratios improved significantly when diets were supplemented with meth and arg. Wang et al. (2005) reported that cricket meal replaced partial protein supplement on an equal of CP percentage and TMEn basis, broilers BWG, FI and gain:feed ratio from 8 to 20d post-hatching were not significantly affected among diets 5% (351 g, 586 g & 0.618 g/kg, respectively), 10% (357 g, 575 g & 0.621 g/kg, respectively) and 15% (351 g, 576 g & 0.609 g/kg, respectively) cricket meals. Abdul Razak et al. (2012) evaluated the protein quality of house cricket meal using protein efficiency ratio (PER) and net protein ratio (NPR) methods. Treatment diets consisted of basal diet (N-free), basal + cricket meal, basal + SBM and basal + FM. Broiler chicks fed cricket meal diet recorded higher \( P < .05 \) BWG (88.5 g) than chicks fed SBM (81.7 g) but slightly lower than that of FM (92.1 g). Similar trend was observed in gain:feed ratio among treatments. The PER values for cricket meal, SBM and FM were 3.42, 3.11 and 3.71, respectively. NPR values for cricket meal, SBM and FM were 3.66, 3.29 and 3.96, respectively. The PER and NPR values of house cricket meal were higher \( P < .05 \) than that of SBM but slightly lower than that of FM. The results suggested that the house cricket meal has a considerable amount of protein and energy which could be included in poultry diets.

### 9. Silkworm

Other common names are silkworm pupae (SWP), silkworm meal, spent silkworm pupae, defatted silkworm pupae meal, deoiled silkworm pupae meal, non-defatted silkworm pupae meal, non-defatted silkworm pupae meal, spent silkworm pupae, defatted silkworm pupae meal, and Muga silkworm pupae meal. A number of species of silkworm are known as *Bombyx mori* Linnaeus; *Antheraea assamensis*; *Antheraea mylitta*; *Antheraea paphia; Samia cynthia ricini* (Makkar et al. 2014). The SWP are available after the removal of silk cocoons through spinning or reeling as discarded waste in large quantities (Khatun et al. 2005). Similarly, silkworm caterpillar is not a worm but the caterpillar of moth butterfly (*Bombyx Mori*) whose cocoon is used to make silk (Ijaiya and Eko 2009). The world’s 90% production results from the
coconuts of the domesticated mulberry silkworm *Bombyx mori*. Silkworm caterpillar hatches from a tiny black egg laid by the adult moth. It nourishes on mulberry and shear butter leaves constantly and grows to full size of 7.5–10 cm within 4–6 wks ([Ijaiya and Eko 2009]).

### 9.1. Chemical composition

The SWP is a waste product of silk industry that could be used as a top class unconventional protein and energy source for poultry diets after proper processing at a reasonable cost. Mishra et al. (2003) reported that the proximate compositions for SWP on fresh basis were found in the range of moisture (65–70%), CP (12–16%), EE (11–20%), carbohydrate (1.2–1.8%), and ash (0.8–1.4%). The energy contents of the SWP were in the range of 706–988 kJ. Zhou and Han (2006) reported that the dried SWP powder contained 71.9% CP, 20.1% EE and 4.0% ash on a DM basis. In another study, the percentages of CP and EE contents (DM basis) were 55.6 and 32.2, respectively (Tomotake et al. 2010). The mineral analysis indicated high K content with a low Na/K ratio and low heavy metal content. Longvah et al. (2011) reported that proximate composition of Eri silkworm pre pupae and pupae as a good source of CP (16 g %), EE (8 g %) and minerals on fresh basis. The high CP content in the defatted Eri silkworm meal (75%) with 44% total EAAs makes it an ideal candidate for preparing protein concentrate isolates with enhanced protein quality that can be used in poultry diets. Zhou and Han (2006) reported that the SWP protein contained 18 known AAAs, including all of the EAAs and sulphur-containing AAAs. Compared with the AA profile recommended by FAO/WHO, the pupal protein was of high quality due to its high content of EAAs. Longvah et al. (2011) reported that the AA scores of Eri pre pupae and pupae protein were 99 and 100 respectively, with leucine as the limiting AA in both cases. Net protein utilization of pre pupae and pupae was 41 as compared to 62 in casein. Protein digestibility corrected AA score was 86. Kotake-Nara et al. (2002) reported that the total lipid content of the SWP was 4.8 and 9.0% for the male and female (wet basis), respectively. The SWP contained carotenoids (lutein and neoxanthin) that may also act as antioxidant in total lipids. The SWP contained n-3 FAs, especially α-linolenic acid (36.3%), as a major component (Tomotake et al. 2010). Kwon et al. (2012) also reported that FA composition of SWP oil revealed a high ratio of EFAs (α-linolenic acid + linoleic acid; 49.0%) and non-essential FAs (19.9% oleic acid, 2.5% palmitoleic acid, 19.7% palmitic acid, 8.6% stearic acid and 0.3% eicosapentaenoic acid).

### 9.2. Effect of silkworm on poultry performance

Banday et al. (2009) reported that the broilers fed with processed SWP at both 25 and 50% levels showed an increase (P < .05) in BWG and improved FCR as compared to raw SWP. Ijaiya and Eko (2009) replaced FM (by 25, 50, 75 and 100%) with silkworm caterpillar meal in broiler finisher diet. There were no significant differences in performance in terms of FI (95.71–98.25 g), BWG (46.10–98.51 g), FCR (1.98–2.08) or protein efficiency ratio (2.41–2.54) between dietary treatments. Silkworm caterpillar meal proved less expensive (cost/kg of gain = 0.16 US$) at 100% replacement than conventional FM (cost/kg of gain = 0.19US $), making it well suited in economic terms as a substitute. Khatun et al. (2003) formulated broiler’s diet containing control diet (6% FM + 0 SWP) and three treatment diets (4% FM + 2% SWP; 2% FM + 4% SWP and 0% FM + 6% SWP). They reported that the BW (1274.24, 1425, 1440.15 and 1474.99 g/bird, respectively at 42d of age), FCR (2.25, 1.95, 1.93 and 1.88, respectively), dressing percentage (58.75, 68.15, 69.37 and 73.0, respectively) and profitability (0.15, 0.19, 0.21 and 0.22 US$/kg broiler, respectively) increased linearly on increasing level of SWP. In another study, the BWG of Rhode Island Red (RIR) layer chicks was found high (26.7 g/day) when fed diet containing 50% FM + 50% SWP (Dutta et al. 2012). Khatun et al. (2005) fed iso-nitrogenous and isocaloric diets containing control diet (6% protein concentrate + 0% SWP) and two treatment diets (0% protein concentrate + 6% SWP and 0% protein concentrate + 8% SWP) to RIR layer chicks. They reported that the BW (1406, 1500 and 1450 g/bird, respectively at 45 wks of age), FCR (2.25, 1.95, 1.93 and 1.88, respectively) and feed cost/bird (1.10, 0.87 and 0.87 US$, respectively), egg production (79.25, 81.50 and 79.33%, respectively from 28 to 45 wks on hen day basis) and feed efficiency (2.26, 2.10 and 2.24, respectively). The above results revealed that growth, egg production and profitability were significantly higher in birds fed 6% SWP diets as compared to birds fed other diets. Recently, Ullah et al. (2017a) evaluated broiler’s diets containing control diet (100% SBM + 0 SWP) and four treatment diets (75% SBM + 25% SWP; 50% SBM + 50% SWP; 25% SBM + 75% SWP and 0% SBM + 100% SWP). Live BW and FI were higher (P < .05) in birds fed diet containing 25% SBM + 75% SWP group (2143.3 g and 4572.4 g, respectively) than other groups. However, FCR and dressing percentage were similar (P > .05) among the all groups. Cost per kg of feed steadily declined (P < .05) with increasing dietary level of SWP inclusion levels (0.41, 0.40, 0.39 and 0.38 US$, respectively), indicating higher economic benefit. However, the gross return per bird and profit per kg meat were higher for diet containing 25% SBM + 75% SWP group (2.95 and 0.65 US$, respectively). In another study, same scientists (Ullah et al. 2017b) conducted a feeding trial in laying hens (52 wks old) for 42 days and replaced SBM with SWP meal in the same ratio as mentioned in the above study. The results showed that BW, daily FI, hen day production, average egg weight and FCR did not differ significantly (P > 0.05) among the dietary groups. Apparent total tract digestibility of nutrients was not different in the control group compared to treatment groups. Blood profile and egg quality parameters also showed no significant (P > .05) differences among dietary groups. Based on above two studies, it could be concluded that SWM can be effectively used as an alternative protein source to SBM without any adverse effects on broiler as well as layer performance. The literature implied that improved performance of broilers with the replacement of FM or SBM with SWP could be related to their higher content of EAAs (particularly tryp), minerals, energy, nutrient digestibility and an increased rate of protein accumulation (Khatun et al. 2003; Ullah et al. 2017a). Moreover, Fagooone
arg: 4.86%; leu: 4.08%; isoleu: 3.11%; phy: 3.45; thr: 2.31%).

were EAAs (lys: 6.13%; meth: 1.58%; val: 5.22%; hist: 2.80%;
arg: 4.86%; leu: 4.08%; isoleu: 3.11%; phy: 3.45; thr: 2.31%).

Most abundant FAs were found as linolenic acid (35.82%) and stearic acid (35.40%).

10.2. Effect of Cirina forda on poultry performance

Oyegoke et al. (2006, 2013) conducted two trials for determining the performance of broiler chicks to the replacement of FM (30, 50, 70 and 100%) with the larvae of Cirina forda. The results showed that the FI, BWG of birds fed diets containing larvae did not differ significant when compared with the control diet (100% FM) at the starter or finisher phases. The cost of diet supplied to the broiler with lower content of Cirina forda (30%) was marginally cheaper than the cost of diet consumed by birds with higher content of Cirina forda (70% or 100%); an indication that decreasing levels of Cirina forda incorporation in the diets of broiler may lead to lowering costs of diet production and hence, economically advisable in formulating diets of broilers. Amao et al. (2010) evaluated westwood larvae meal (WWLM) on laying performance and egg characteristics of hens and concluded that it can replace up to 75% FM in the diet of laying hens without affecting FI, BWG, egg production, feed efficiency and egg quality characteristics. Hen day production of birds fed 0% WWLM (77.86%), 25% WWLM (78.32%), 50% WWLM (77.82%) and 75% WWLM (77.37%) were similar but higher (P < 0.05) than that of those fed 100% larvae meal (73.39%). The data showed that at 100% replacement, daily egg production, egg weight and efficiency of feed utilization were significantly reduced. Thus the larvae powder represents a potential alternative for the highly nutritious and rather expensive FM.

11. Conclusions

Due to high nutritional value and ubiquitous presence, insects are a potential sustainable feed resource in poultry nutrition. Generally results of studies confirm the feasibility of total or partial replacement of FM with insect meal. In particular, no negative effects have been reported on growth of insect meal-fed poultry, however most of papers have described similar or even better growth rates in chicks when compared to SBM or SBM plus FM. In the same way the digestibility of nutrients seems to be unaffected, or at least improved, by the use of insect meal in poultry diet when compared with FM: this is especially true when insect meal has a comparable AAs profile and replaces the whole FM in the diet determining some economical positive effects. The costs of conventional feed materials such as SBM and FM are very high demand and moreover, future availability may be limited. The inclusion of insect meals in poultry diets may lower the cost of feeds, thus contributing to the more profitability of smallholder poultry production. Further research efforts are necessary to deeply investigate the impact of different insect meal on intestinal morphology. In addition, the effects of insect feed on meat quality traits and sensory properties should be carefully investigated for both consumers acceptance as well as for marketing purposes. Further research on long-term feeding effects including laying hens before and during peak of lay and on resulting egg quality is necessary to approve insects as a practicable source of feed protein.

Disclosure statement

No potential conflict of interest was reported by the author.

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