Chapter 10

Brief Summary of Insect Usage as an Industrial Animal Feed/Feed Ingredient

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Chapter Outline

OVERVIEW

Justification of Using Insects in Animal Feed

The production of food from animal origins has become increasingly expensive in economic and environmental terms. This situation is mainly provoked by increased demand because of increasing human populations and changes in human diets, both of which lead to increases in the demand for and ingestion of animal-derived products. Global demand for meat products will increase by 58% between 1995 and 2020, and meat consumption will rise from 233 million t (metric tons) in 2000 to a possible 300 million t by 2020. Milk consumption will increase from 568 to 700 million t by 2020, and there will be an estimated 30% increase in the demand for egg production (FAO, 2004a).

Animal feeding is one of the most expensive aspects of animal production, and it is very damaging from an environmental point of view. The global production of animal feed is estimated at about 1000 million t/year, including 600 million t of compound feed (FAO, 2004a). Moreover, it was identified as a major contributor to land occupation, primary production (the net amount of biomass produced each year by plants) use, acidification of soil, climate change, energy use, and water dependence (Mungkung et al., 2013).

The nutritive needs of monogastric species include high quality and high quantities of protein in the diet. From a nutritional point of view, in addition to stable quantity and quality production, protein sources must have high protein content, an adequate amino acid profile, high digestibility, good palatability, and no antinutritional factors (Barrows et al., 2008). Currently, the principal protein sources for animal feed are fishmeal (fish meal) and soy meal, and both products are linked

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to environmental problems. Soy cultivation causes the deforestation of areas with high biological value (Carvalho, 1999; Osava, 1999), high water consumption (Steinfeld et al., 2006), pesticide and fertilizer utilization (Carvalho, 1999), and transgenic variety usage (Garcia and Altieri, 2005), which cause significant environmental deterioration (Osava, 1999). On the other hand, fish meal is a resource that depends on the catch. The deterioration of the marine environment and the stripping of fisheries have resulted in decreased fish meal production, and its production is therefore quantitatively and qualitatively variable (AFRIS, 2015). In addition, an increase in demand has led to higher prices, including an increase from $600USD/t ton in 2005 to $2000USD/t to in June 2010. This trend of increasing prices is likely to continue (International Monetary Fund, 2010), because the prohibitive costs of feed (eg, meat meal, fish meal, and soybean meal) are major constraints to further development.

Change and innovation are required in many livestock production systems if they are to meet the present and future demands for animal products. In this context, research on and commercial implementation of new feeds (especially those rich in protein) for animal feeding is needed for sustainable animal production.

Several by-products and wastes from different industries have been examined for their potential as animal feed options with variable results, and they allow different inclusion levels of ingredients, thus saving traditional feed. Nevertheless, the variable quality and limited production are two important constraints.

Currently, there is great interest in the role of insects in animal feeding. Nutritive composition studies showed that insect protein values in most species have high protein quality and quantities (Ladrón de Guevara et al., 1995; Ramos-Elorduy et al., 1981, 1982, 1984, 1997). Studies of the protein percentages of numerous insect species revealed many species with higher protein levels than fish meal or soy meal. The highest values were found in the coleopteran [cactus weevil (*Metamasius spinolae* Gyllenhal, 69.1%) and *Rhantus atricolor* Aubé, 71.1%], dipterous [common fruit fly (*Drosophila melanogaster* Meigen, 70.1%)], and orthopteran orders (*Boopedon flaviventris* Bruner, 76.0%), (*Melanoplus mexicanu*s Saussure, 77.1%), and (*Sphenarium histrio* Gerstaecker, 74.8%) (Sánchez-Muros et al., 2014). In addition to their nutritive qualities, the utilization of insects as feed implies certain environmental benefits such as high food conversion. Insects also feed on organic wastes, which could aid in the recycling of organic matter. Furthermore, compared to livestock, the use of insects could lead to the reduction of released greenhouse gasses (Oonincx and de Boer, 2012) and ammonia, and it could lead to decreased land occupation and water consumption (van Huis et al., 2013).

We can find many studies in the scientific literature that evaluate insect ingredients in animal feed. There is also a growing commercial interest in insects as animal feed, and the research is conducted in parallel with the increasing costs of traditional raw materials (López-Vergé et al., 2013). However, if we want to determine the nutritional potential of insects, research cannot only focus on their chemical composition (percentage of fat or protein and amino acid or fatty acid), it is also necessary to evaluate the nutritive and physiological utilization. Feeding trials in different species are needed to determine their future role as protein components in animal feed. As Finke et al. (1985) argued, the evaluation of protein quality through bioassay techniques is a more precise indicator of limiting amino acids than amino acid analyses. It is incorrect to think that only the proportion of each type of amino acid in each insect species can indicate its protein quality.

On the other hand, the potential of insect in animal feeding is not only defined by the nutritive characteristics. Although there are several companies reaching impressive scale and low prices for black soldier fly larvae, the need for mass production of various species of insects cheaply and with lower environmental impact is probably one in major need of research.

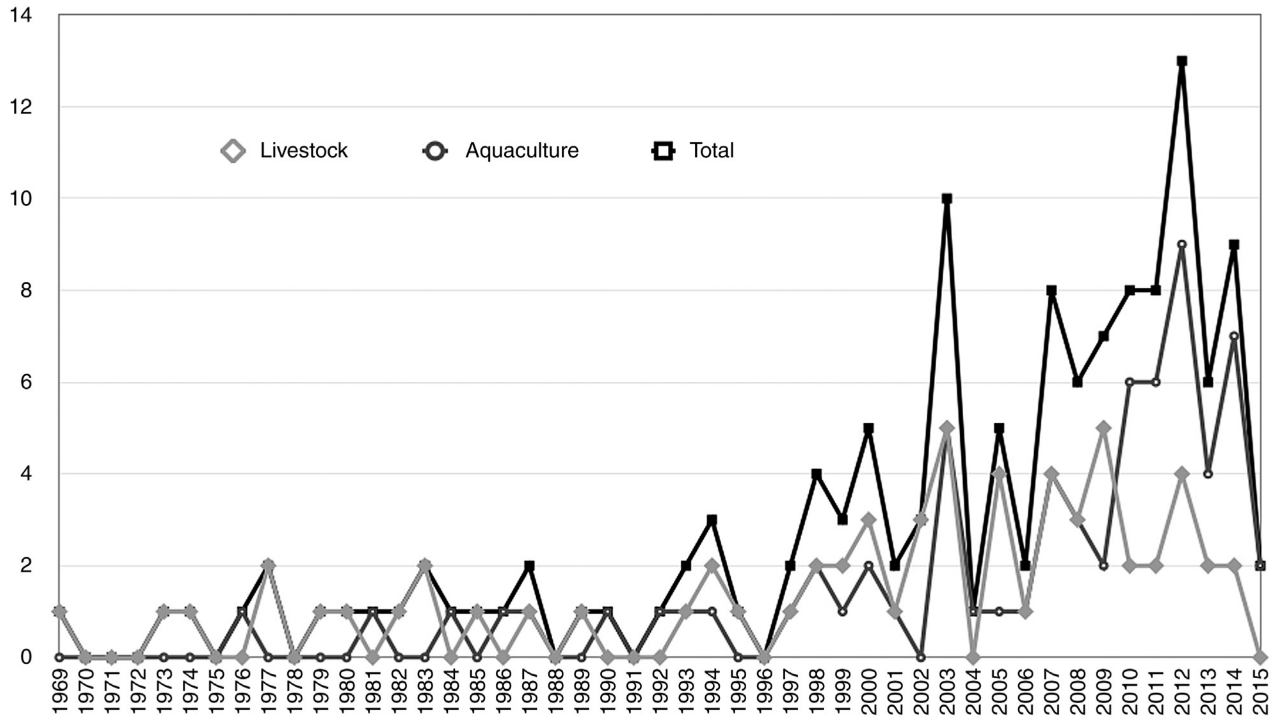
Current Overview of the Use of Insects in Animal Feeding

It is reasonable to assume that the number of scientific publications on the use of insects as animal feed has increased in recent years, and the numbers of papers found on this topic indicate that this is the case (Fig. 10.1). For instance, the number of publications in the last 15 years (2000–15) has tripled relative to the previous 30 years (1969–99). During the first 8 years of the 21st century (2000–07), there were 34 publications, and there were 56 publications during the next 8 years (2008–15). This trend suggests that the production of publications will continue to increase.

Another important aspect is that scientific interest is higher for some types of animal production, particularly in aquaculture production. Therefore, while the number of livestock feeding experiments has doubled in the past 15 years, the number of feeding experiments in aquaculture has quadrupled.

The increased interest in insects as an alternative protein source is probably due to the increased cost and limited availability of fish meal, which is the ideal protein ingredient in animal feed. The role of fish meal in the formulation of commercial aquaculture feed is higher than in feed for livestock, and this could explain why the number of feeding studies in aquaculture is much higher than in livestock.

The nutritional potential of up to 24 different species of insects belonging to 6 different orders (Blattodea, Coleoptera, Diptera, Isoptera, Lepidoptera, and Orthoptera) has been evaluated. However, most publications have tested species from



Period	Livestock	Aquaculture	Total
1969–99	22	13	35
2000–2015	41	54	95

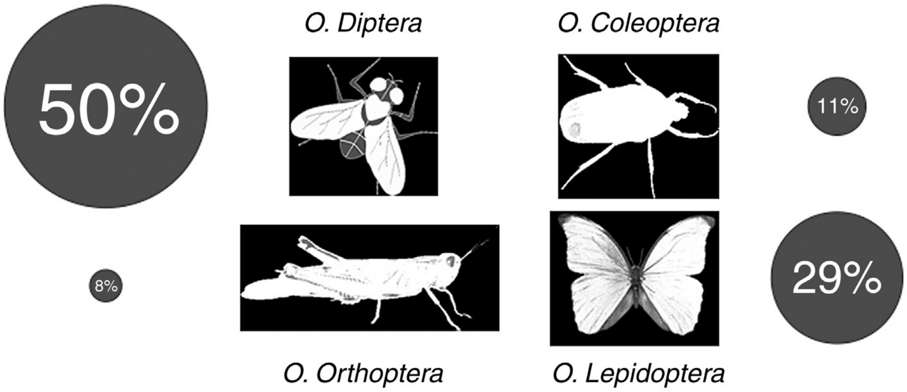
FIGURE 10.1 Papers per year. A literature review was conducted using the number of web publications in the ISI (ISI Web of Knowledge) as a reference, but as there were many articles in nonindexed journals, we had to search in Google academic and other websites in general. The keywords used were as follows: insect meal; animal feeding; livestock; aquaculture; Bombyx; Hermetia; Musca; Tenebrio.

the Diptera (48%) and Lepidoptera (29%) orders (Fig. 10.2). Clear differences between the insects evaluated in the feeding trials for livestock and aquaculture have been observed. In livestock, there is a predominance of experiments with house fly (*Musca domestica* L.; 43%), followed by silkworm/silkmoth (*Bombyx mori* L.;15%). However, that predominance is not so clear in aquaculture. Although experiments with the house fly (34%) are the most abundant, a similar number (29%) have evaluated silkworm. Furthermore, studies on other species (eg, black soldier fly, *Hermetia illucens* L., and yellow mealworm, *Tenebrio molitor* L.) are also common.

Lastly, we want to focus on the location of research studies (Fig. 10.3). Although experiments have been conducted in 27 countries, most of the studies are conducted in 10 Asian (40%) and 7 African countries (34%). In Asia, countries such as India (15%) and China (12%) are highlighted, but most of the feeding trials in Africa have been conducted in Nigeria (29%). It seems clear that the potential of insects as animal feed has been further investigated in this African country, because one-third of studies worldwide were conducted in Nigeria.

It should also be noted that researchers in the United States have conducted 12% of the feeding studies, but there is a downward trajectory to research conducted in this country. For instance, 10 studies were carried out before 2000, but only 4 were conducted after that date. In contrast, the interest observed in European countries seems to be increasing in recent years, and 12 (out of 13 total studies) have been published since 2000.

Besides gains in scientific development, there has been an increase in the number of companies that produce insects as pet feed and also products derived from insects. Nodaways, the major number of stakeholders is located in Europe (157, mainly research), followed by the United States (56). A growing interest in insects as an alternative protein source has also led to the establishment of companies in the Netherlands, Spain, South Africa, and the United States. More complete information can be found at the following website: http://www.fao.org/forestry/edibleinsects/stakeholder-directory/en/.



Insects used in *livestock* food

Insect species	Order	%
Musca doméstica	Diptera	43
Bombyx mori	Lepidoptera	17
Antheraea assamensis	Lepidoptera	6
Hermetia iluscens	Diptera	6

Insects used in *aquaculture* food

Insect species	Order	%
Musca doméstica	Diptera	34
Bombyx mori	Lepidoptera	29
Hermetia illuscens	Diptera	13
Tenebrio molitor	Coleoptera	9

FIGURE 10.2 Insects used in animal food (% papers).

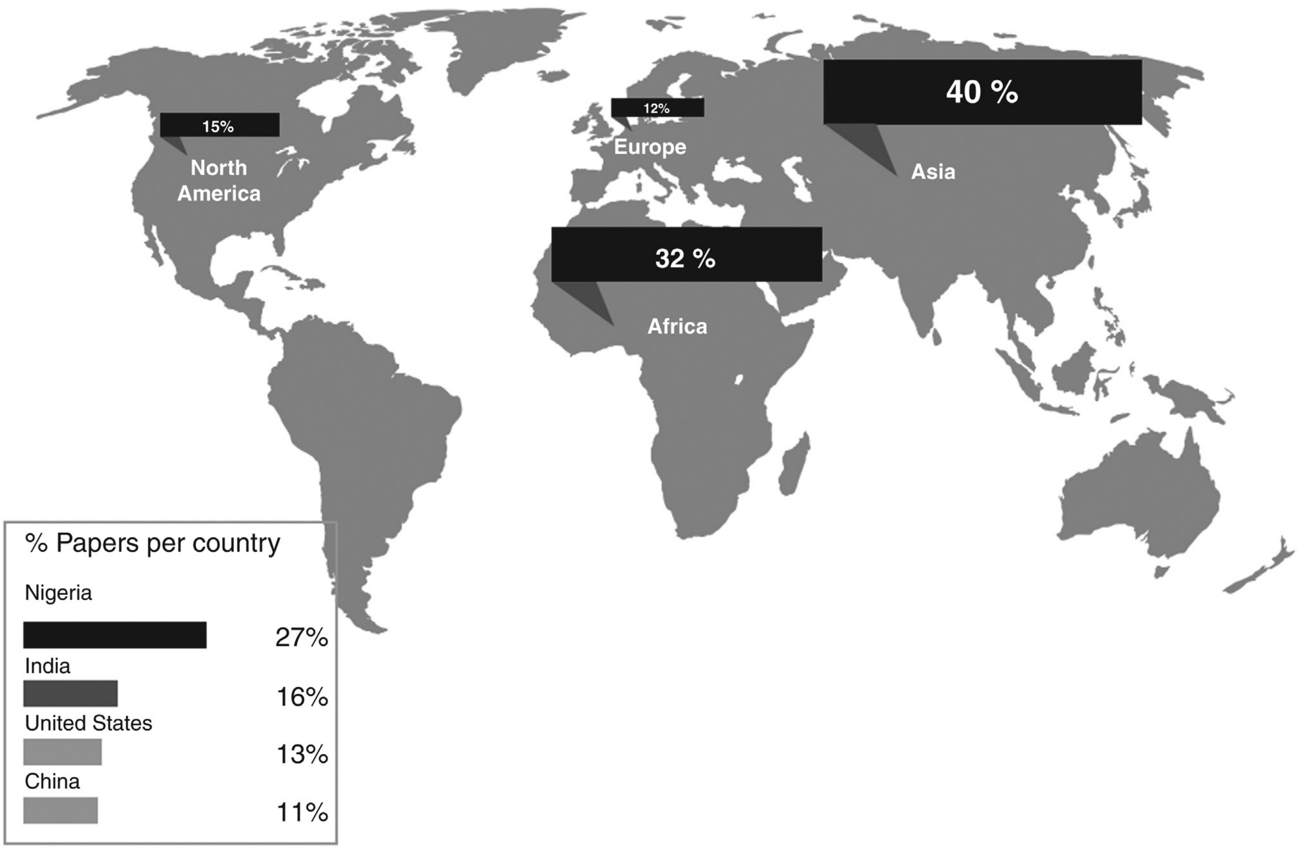


FIGURE 10.3 Geographic distribution of papers.

EXAMPLES OF LIVESTOCK FED WITH INSECTS AS FEED INGREDIENTS

Poultry

In contrast to ruminant livestock production, the major problem facing the poultry industry is a food supply that will contain all diet components needed by birds for rapid growth within a short period of time (Oyegoke et al., 2006). This is because birds are monogastric, and hence they lack the complex digestive anatomy for the synthesis of proteins and vitamins that is found in ruminants (Adeniji, 2007). Therefore, soybean meal is the major protein source of their diet, and it is supplied together with fish meal, which covers any amino acid deficiency associated with vegetable proteins (Miles and Jacobs, 1997). Thus, fish meal is a very important feed ingredient in poultry production (Ijaiya and Eko, 2009).

The animal protein source is the most costly ingredient for the formulation of poultry diets compared to other nutrient sources (Khatun et al., 2003). Soybean meal and fish meal are expensive, and our ability to replace them is limited. Therefore, the search for alternative sources used for total or partial replacement in the future is an important task (Ramos-Elorduy et al., 2002). The search for alternative and sustainable proteins is an issue of major importance that needs viable solutions in the short term, and this makes insect meal an increasingly attractive feed option for poultry (Makinde, 2015). In contrast to fish, wild birds and free-ranging poultry naturally consume many insects (Zuidhof et al., 2003), especially during their early life stages. For example, chickens can be found picking worms and larvae from the topsoil and litter where they walk (van Huis et al., 2013).

Although there are some very interesting reviews on insect use in poultry feeds (Khusro et al., 2012; Makkar et al., 2014; Veldkamp & Bosch, 2015), we have atempted to update the maximum number of publications on this subject in the next section. We believe that the most important contributions to this subject are presented here, but a number of articles have been difficult to access because of their local interest and distribution.

*Broiler Chickens (*Gallus gallus domesticus *L.)*

Order Blattodea (Cockroaches)

***American Cockroach* (Periplaneta americana *L.*)** The only feeding trial with cockroaches was conducted by Aigbodion et al. (2012) who fed broilers insect diets enhanced with American cockroach adults. These researchers obtained significantly higher growth at 8 weeks with a diet containing cockroaches.

Order Coleoptera (Beetles)

Unlike the studies on maggots or silkworms, there are limited feeding trials on the use of mealworms or other beetle species in poultry diets.

Maize Weevil (*Sitophilus zeamais* Motschulsky)

López-Vergé et al. (2013) studied the effects of adding *maize weevil* larvae to the diet on performance parameters. The animals were divided into two treatment groups (insect-infested diet and an untreated diet as the control). The broiler chickens fed the insect-infested diet had a higher final body weight and a higher average daily feed intake than did animals fed the control diet. Furthermore, they did not detect pathogens in the insect (neither *Salmonella* sp. nor *Listeria monocytogenes* [Murray]), and hence concluded that maize weevil could be a safe ingredient.

Yellow Mealworm (*T. molitor*)

Ramos-Elorduy et al. (2002) found that yellow mealworms had potential usage as a protein source for raising broilers. Feeds with three percentage levels of mealworms (0, 5, and 10% dry weight) were used in a 19% protein content sorghum-soybeanmeal-based diet. They found no significant differences in feed intake, weight gain, or feed efficiency among the treatments.

Ballitoc and Sun (2013) conducted other experiments to determine the growth performance and carcass characteristics of broiler chicks fed with feed containing different percentage levels of ground yellow mealworm larvae. The study used five treatments at inclusion levels of 0, 0.5, 1, 2, and 10% yellow mealworm to replace commercial feed. They concluded that supplementation with ground yellow mealworms produced an increase in feed intake, body weight, and the efficiency of feed consumed due to a lower feed conversion rate (FCR). However, the best performing inclusion level was low (2% ground yellow mealworms).

Order Diptera (Flies)

***Black Soldier Fly* (H. illucens)** Oluokun (2000) examined the effects of treatments with either fish meal or black soldier fly larvae meal regarding a full-fat soybean meal diet as a control. The average live weight gains of broilers fed with fish meal or black soldier fly larvae meal were higher than those fed the control diet. Oluokun also reported that the diet upgraded with the larvae meal did not affect the rate of gain, feed consumption, or the feed/gain ratio regarding fish meal. Moreover, there were improvements in the carcass yield, internal organ measurements (kidney, gizzard, and liver), and abdominal fat in animal feed with larvae diet regarding fish meal or control diet. Then the author concludes that maggot meal could replace fish meal in the broiler rations without any adverse effect on zootechnic indices.

Elwert et al. (2010) conducted a study during the starter and grower phases of broilers. In the starter phase, all-vegetable (wheat-corn-soybean meal) and fish meal diets (3% fish meal) served as negative and positive controls, respectively. In the test diets, different black soldier fly larvae meal proportions, depending of different level of defatting, were supplemented: 6.6% black soldier fly larvae meal with a fat content of 37%, 5.4% black soldier fly larvae meal with a fat content of 22%, and 4.7% black soldier fly larvae meal with a fat content of 15%. During the starter period, the full fat *Hermetia* meal (crude fat 37) yielded similar high body weights as compared to the fish meal diet. However, during the grower phase, the results comparing all-vegetable diets and a partially defatted diet (5% black soldier fly larvae meal, crude fat 22) did not lead to clear conclusions.

House Fly (*M. domestica*)

House fly maggots (*M. domestica* larvae) are most commonly used as feed for poultry. In many rural areas of the world, maggots have always constituted part of the daily diet of scavenging poultry (Téguia et al., 2002). Thus, maggot meal has been included in broiler diets as a replacement for conventional protein sources (Makinde, 2015). Calvert et al. (1969) found that a corn-house fly diet led to a slight (but not significant) improvement in the growth rate of chicks compared to a conventional corn-soybeanmeal diet.

In general, most of the studies using maggot meal have described similar or improved growth rates in chicks as compared to that resulting from vegetable meals. Teotia and Miller (1973) found no significant differences in final body weights or feed/gain ratios between chicks fed house fly pupae diets and those fed soybean meal control diets. Hwangbo et al. (2009) used a corn-soybean diet as basic feed (control), and diets supplemented with 5.0, 10.0, 15.0, or 20.0% maggot meal were used as experimental feed. They also found that diets containing 10–15% maggot meal improved the carcass quality and growth performance of broiler chickens.

Pro et al. (1999) used two sorghum diet treatments with maggot meal (24 and 19% for starter and grower phases, respectively), and soybean meal (38 and 32% for starter and grower phases, respectively) was used as a control. Although the maggot meal inclusion rate was high, there were no differences in body weight gain, feed consumption, and feed efficiency between the two treatments.

Adeniji (2007) investigated the replacement value of maggot meal for groundnut cake (GNC) in broiler diets. Several experiment diets were used in this study with increasing maggot meal inclusions (up to 22% of the diet). The results of this experiment indicated that broilers tolerated the 100% maggot meal replacement in their diet without adverse effects on performance. However, there were no significant differences in weight gain, feed intake, feed/gain ratio, or nutrient retention.

Adesina et al. (2011) evaluated the performance of broilers fed cassava peel-maggot meal mixture as a partial or total replacement for maize. In particular, they used a 4:1 ratio of dry cassava peel to maggot meal. The weight gain to FCRs were similar in the broilers fed the control diet (0% peel-maggot meal mixture) and the 50% peel-maggot meal mixture (29% diet). Regarding the cost of production, they also observed a significant reduction in the total feed costs when the peel-maggot meal mixture mixture was included (up to a 50% replacement).

Maggot meal has also been used to replace meat meal in broiler diets. Bamgbose (1999) used a control diet with meat meal (8% diet) and maggot meal with 0, 50, and 100% replacement levels with or without methionine. He concluded that maggot meal could completely replace meat meal without any adverse effects on performance and nutrient utilization. Moreover, nutrient utilization and performance were significantly enhanced with methionine supplementation (0.20%).

Several feeding trials have been conducted to evaluate the performance of broiler chickens fed maggot meal as a replacement of fish meal. In a yellow maize-soy meal diet, part of the soy was replaced by either maggot meal (4% of the diet) or fish meal (3% of the diet) (Ocio et al., 1979). No significant differences were found for weight increase or FCE between the three experimental groups. In a similar experiment, Ren et al. (2011) divided chickens into three groups: control, basal diet supplemented with 4% fish meal, and basal diet supplemented with 4.44% maggot meal. The results showed that the average daily weight gain and daily feed intake for the house fly larvae meal (maggot meal) group were significantly higher than those of the fish meal and control groups at the small broiler stage.

On the other hand, Djordjevic et al. (2008) used a 5% fish meal diet as a control. Experimental diets included those with a 50% fish meal substitution (2.5% fish meal-3% MGM), a 100% fish meal substitution (0% fish meal-6% maggot meal), and a group supplemented with washed fresh housefly larvae without fish meal or maggot meal. The results indicated that the substitution of fish meal with housefly larvae had no negative effects on body mass, daily weight gain, or food conversion. However, the most interesting result was that broilers from the experimental group supplemented with washed fresh housefly larvae had the highest feed intake. As Djordjevic et al. (2008) pointed out, this result is probably associated the physiological and biological characteristics of birds.

Okah and Onwujiariri (2012) formulated five diets where fish meal (4% of the diet) was replaced with 0 (control diet), 20, 30, 40, and 50% maggot meal. They observed that the highest substitution used (2% fish meal and 2% maggot meal) showed superior performance characteristics compared to the control diet (4% fish meal), and it was also proven to be a more economical option. The cost of diets decreased with increased levels of maggot meal. A live weight kilogram of the birds fed the 50% dietary maggot meal was 34.22% cheaper than those fed the control diet (4% fish meal). Similarly, Pieterse et al. (2014) investigated the effects of three diets containing 10% fish meal, 10% maggot meal, or a control diet with soybean meal as the protein source on broilers. Chicks that received the control diet had significantly lighter carcasses and a lower breast meat yield than either the 10% maggot meal or 10% fish meal chicks.

Conversely, neither Atteh and Ologbenla (1993), Awoniyi et al. (2003), nor Okubanjo et al. (2014) obtained such satisfactory results. They observed that maggots only provided a partial replacement for fish meal in broiler diets. For instance, Atteh and Ologbenla (1993) examined the effects of replacing 0, 33, 68, or 100% of dietary fish meal (9% of diet) with maggot meal. They noted that increased dietary levels of maggot meal reduced weight gain, and that maggot meal could only replace 33% of dietary fish meal to obtain comparable results to those of the control diet with fish meal. In a similar experiment, Awoniyi et al. (2003) used a control diet with 4% fish meal, and the treatment diets were formulated with maggot meal replacing 0, 25, 50, 75, and 100% of the fish meal. They reported that production rates tended to decrease with increasing levels of maggot meal replacement, and the 25% level of fish meal replacement with maggot meal (3% fish meal and 1.17% maggot meal) was the best replacement level. Moreover, Okubanjo et al. (2014) used maggot meal to replace fish meal at 0, 25, 50, 75, and 100% levels, which constituted 0, 1.4, 2.7, 4.1, and 5.4% of the diet, respectively. As in previous experiments, the final live weight decreased with the higher levels of dietary maggot meal, and only a 25% substitution of fish meal (1.4% maggot meal) showed no significant difference compared to the control diet.

There are several studies that examined the effects of maggot meal on broiler meat quality and carcass characteristics. Teotia and Miller (1973) incorporated houseflies into broiler diets, but did not detect any differences between chicks fed the control and experimental diets based on an informal taste panel. Ren et al. (2011) also observed no negative effects on the slaughter performance and meat quality associated with the incorporation of maggot meal in the diets.

Awoniyi et al. (2003) also observed that maggot meal (maggot meal) supplementation had no significant influence on dressing percentage, leg muscle yield, or breast muscle yield. These results were in agreement with the findings of Téguia et al. (2002), but they differed from the findings of Hwangbo et al. (2009). Hwangbo et al. (2009) found that the use of maggot meal had no effect on breast meat color, but it improved the dressing percentage compared to a corn-soy diet. According to Makinde (2015), these contradictory reports could also be attributed to the trial design where Hwangbo et al. (2009) had 30 replicates per treatment relative to the 6 and 4 replicates of Awoniyi et al. (2003) and Téguia et al. (2002), respectively.

Moreover, Okubanjo et al. (2014) also found no significant effects on organoleptic flavor, color, overall acceptability scores, and meat/bone ratios in broilers when maggot meal replaced fish meal (4.5% of diet), but sensory tenderness and juiciness were significantly higher with diets containing maggot meal. Pieterse et al. (2014) compared diets containing either 10% fish meal, 10% maggot meal, or a control diet with soybean meal, and reported no differences in breast and thigh muscle color, pH, water holding capacity, or cooking losses among the treatments. However, they observed significant differences in drip loss with the highest fish meal-fed samples (followed by the control diet), and the lowest drip loss was reported for the maggot meal-fed samples. Based on these results, it appears that the inclusion of larvae meal into the diets of broilers could have positive, rather than detrimental, effects on most carcass, meat, and sensory characteristics.

Order Lepidoptera (Butterflies, Moths and Their Caterpillar Larval and Chrystalis/Pupal Stages)

In a feeding trial for broilers, Ijaiya and Eko (2009) replaced 100% fish meal (8.75% of the diet) with *Anaphe infracta* (Walsingham) meal, and they observed no significant differences in feed intake, body weight gain, FCE, or the protein efficiency ratio. Furthermore, they also observed a decline in the costs associated with increased dietary levels of insect meal.

Muga silkworm, *Antheraea assamensis* Helfer, pupae meal has already been established as an effective protein supplement in broiler rations. The effects of replacing fish meal with muga silkworm pupae meal was examined in several experiments performed at the College of Veterinary Science Khanapara (India), and Sapcota et al. (2003) reported that there were no adverse effects on body weight gain when fish meal (5% level in the broiler diet) was completely replaced with muga silkworm meal. They also observed no adverse effects on various carcass qualities (Sheikh et al., 2005).

Furthermore, according to Sheikh and Sapcota (2007), the production per live weight kilogram of broilers was more economical with diets containing 100% muga silkworm pupae meal supplements. On the other hand, Chaudhary et al. (1998) noted that broiler chicks reared on rations fortified with antibiotics exhibited significantly higher growth rates and improved feed efficiency, and the antibiotic ration was found to be the most economical of the rations studied.

In a study by Sinha et al. (2009), the objective was to compare the growth performance of commercial broiler chicks fed different levels of giant silkworm pupae, *Antheraea mylitta* Drury, meal as an economic substitute for fish meal. The best animal performance was observed in the group fed the 50% silkworm pupae meal/50% fish meal diet.

Silkworm/Silkmoth (*B. mori*)

Within Lepidoptera, most experimental diets were based on silkworm. Silkworm pupae (silkworm pupae meal) are the by-product after the silk thread has been removed from the cocoon. These pupae also commonly serve as human food sources (Jintasataporn, 2012). It is also one of the most studied insect species in recent years regarding its potential use in broiler feeding. Although Fagoonee (1983) suggested that the substitution of fish meal with silkworm pupae meal in broiler chicks depressed consumption due to the high oil and fiber content of silkworms, different feeding trials seemed to indicate that silkworm pupae meal was a good protein source.

The first evidence of a positive effect of the replacement of fish meal with silkworm pupae meal was found by Wijayasinghe and Rajaguru (1977). They conducted three feeding trials to examine the effects of various silkworm pupae meal replacement levels on the performance of broiler and laying hens. Up to 12% silkworm pupae meal was added to the diet, and it was generally observed that fish meal could be successfully replaced by silkworm pupae meal.

In the experiment of Khatun et al. (2003), the chicks were fed four dietary treatments (6% fish meal + 0% silkworm pupae meal; 4% fish meal + 2% silkworm pupae meal; 2% fish meal + 4% silkworm pupae meal; and 0% fish meal + 6% silkworm pupae meal). They observed that the growth rate, feed conversion, liability, meat yield, and profitability increased almost linearly based on increasing silkworm pupae meal levels. Moreover, profits (Tk/broiler and Tk/Kg broiler) were significantly higher as the level of dietary silkworm pupae meal increased.

Dutta et al. (2012) found that broilers fed a mixed diet (50% fish meal/50% silkworm pupae meal) showed improved productive indices. However, the degree of protein fish meal inclusion in the diet was unknown, because they did not include that data in their publication. When they evaluated the economics of feed costs and broiler production, they found that profits increased significantly as the level of dietary silkworm pupae meal increased, and these results were also found in the two previous studies. Similarly, Konwar et al. (2008) pointed out that although silkworm pupae meal can be incorporated into broiler diets by replacing up to 100% fish meal, improved performance was observed in broilers fed 50% fish meal/50% silkworm pupae meal diets with enzyme supplementation.

Using fish meal as reference material, Jintasataporn (2012) evaluated the quality of silkworm pupae from the spun silk industry and from the silk yarn reeling industry on the growth performance, carcass yield, and sensory evaluation of broilers. Although they included up to 20% spun silkworm pupae meal in an experimental diet (0% fish meal/20% spun silkworm pupae meal/0% reeling silkworm pupae meal), treatment with 0% fish meal/5% spun silkworm pupae meal/5% reeling silkworm pupae meal showed no difference in daily weight gain compared to the control diet (10% fish meal/0% spun silkworm pupae meal/0% reeling silkworm pupae meal). However, the results indicated a higher FCR than the control, and the carcass muscle of the control treatment was higher. On the other hand, no significant differences were observed in sensory evaluation.

Another interesting study was conducted by Venkatachalam et al. (1997) on the presence of certain antinutritional substances in defatted silkworm pupae. High amounts of phenols (2%) were found in the pupae, so they were detanned and defatted. In a feeding trial using fish meal (10% of the diet) as the control, detanned silkworm pupae meal and defatted silkworm pupae meal were experimentally tested at 2.5 and 5% levels (of the total diet), respectively. The results indicated that the production rates of chicks were better on diets containing detanned silkworm pupae meal than those containing defatted silkworm pupae meal, and the same results were observed compared to the control.

Ojewola et al. (2005) conducted an experiment comparing a control diet (4% fish meal) with two experimental diets containing pallid emperor moth (*Cirina forda* Westwood) (2% fish meal/2% pallid emperor moth, and 0% fish meal/4% pallid emperor moth). They found no significant differences between the growth performances of the broilers fed on the compound larvae diets compared to those fed fish meal.

Order Orthoptera (Crickets, Grasshoppers, Locusts, and Katydids)

House Cricket (Acheta domesticus) The replacement of soybean meal as the major source of protein by dried house cricket (*A. domesticus*) meal in practical diets doesn't show significant differences in weight gain between chicks fed corn-soybean meal diet and those fed corn-cricket diets. Feed:gain ratios improved significantly when diets were supplemented with methionine and arginine (Nakagaki et al., 1987).

Mormon Cricket (*Anabrus simplex* Haldeman)

High inclusion levels of Mormon cricket have been tested with good results. Thus, DeFoliart et al. (1982) found that corn-cricket-based diets (30% cricket in the diet) produced significantly better broiler chicken growth than that produced by a conventional corn-soybean-based diet. Finke et al. (1985) used crickets directly collected from crops, and also found no significant differences in weight gain in a feeding trial where a corn-cricket diet (including ground crickets at 18–28% of total feed; decreasing during chicken growth) was compared to a corn-soybean meal diet. Moreover, they concluded that, even at high levels, the incorporation of insect protein into the diet had no effect on the carcass quality and the taste of meat. Similar to Nakagaki et al. (1987), Finke et al. (1985) also used this same cricket species, and noted that methionine and arginine were probably colimiting in this insect.

Acrida cinerea (*Thunberg*)

Wang et al. (2007) found that the amino acid content of the grasshopper species *Acrida cinerea* was comparable to that found in fish meal. When maize-insect-soybean meal diets were formulated, the inclusion of 15% of this grasshopper meal did not affect broiler weight gain, feed intake, or the gain/feed ratio. Moreover, Liu and Lian (2003) replaced 20 and 40% fish meal in broiler diets, and observed similar growth rates and feed consumption to those seen in the control diet.

Similar to the results observed in *A. cinerea* experiments, Wang et al. (2005) found that feed containing up to 15% of the cricket *Teleogryllus mitratus* Burmeister could be included in corn-soybean meal diets without any adverse effects on broiler weight gain, feed intake, or the gain/feed ratio. Moreover, their results indicated that the field cricket had considerable amounts of digestible amino acids.

Migratory Locust (*Locusta migratoria* L.)

This locust (grasshopper) species is famous for its seasonal abundance in vast swarms in the wild and occurs in Africa, Asia, Australia, and New Zealand. In a study using increasing replacements of fish meal with the migratory locust (0, 1.7, 3.4, and 6.8% in the diet), the best production rate results were found at 1.7% substitution trials (Adeyemo et al., 2008). Nevertheless, because of the lack of statistical analysis, it is difficult to draw reliable conclusions from this study.

*Laying Hens (*Gallus gallus domesticus *L.)*

Order Diptera (Flies)

House Fy (M. domestica) Parshikova et al. (1981) reported an increase in egg yield when housefly larvae replaced fish meal in the diet of hens. Akpodiete et al. (1998) investigated the replacement value of fish meal with maggot meal (house fly) in the diets of laying chickens using performance indices, egg quality characteristics, and egg yolk biochemistry. A control diet (4% fish meal) was replaced with diets containing 25, 50, 75, and 100% maggot meal. They observed that the maggot meal substitution in the diets of birds did not show adverse consequences on performance and egg quality characteristics for all parameters measured, with the exception of albumen weight. Furthermore, egg yolk cholesterol and calcium concentrations decreased significantly with increased maggot meal inclusion. According to the authors, this may be of nutritional interest regarding the dietetic treatment of patients with atherosclerosis and other cardiovascular diseases.

In a similar experiment, Agunbiade et al. (2007) used fish meal and maggot meal as animal protein sources to supply the remaining 25% of the total dietary protein: 25% fish meal/0% maggot meal, 18.75% fish meal/6.25% maggot meal, 12.5% fish meal/12.5% maggot meal, 6.25% fish meal/18.75% maggot meal, and 0% fish meal/25% maggot meal. Although the average daily feed intake, weight gain, and FCR were not significantly affected, hen-day egg production was significantly influenced by the dietary treatments. The 12.5% fish meal/12.5% maggot meal diet showed the highest hen-day production, and the authors thought this could be a result of the complementary effects of the maggot meal and fish meal amino acid profiles. Moreover, regarding egg quality, they found that eggs from birds on diets containing maggot meal exhibited a linear decrease in shell thickness and shell weight. They concluded that the lower calcium content of maggot meal compared to fish meal was a feasible explanation.

Although the work of Dankwa et al. (2002) was conducted using rural poultry instead of laying hens, we are including it here because they studied the effects of supplementing the diet of scavenging chickens with live maggots on productivity (eg, body weight, age at first lay, egg weight, number of eggs hatched, and weight of chicks hatched). The experiment lasted for 14 months, and the experimental group of birds was supplemented with 30–50 g of live housefly larvae. They reported that clutch size, egg weight, number of eggs hatched, and chick weight were significantly higher in supplemented birds than in control birds. Previously, Ekoue and Hadzi (2000) found that the movements of live larvae stimulated consumption by chickens.

Order Lepidoptera (Butterflies, Moths, and Their Caterpillar Larval and Chrystalis/Pupal Stages)

Silkworm/Silkmoth (B. mori) To determine the effects of silkworm pupae meal on the growth and egg production performance of Rhode Island Red chickens, Khatun et al. (2005) compared layer chicks fed three dietary treatments (6% protein concentrate (PC) + 0% silkworm pupae meal; 0% PC + 6% silkworm pupae meal; and 0% PC + 8% silkworm pupae meal). In this study, the values of the most significant parameters (ie, profitability, growth, and egg production performance) were significantly higher in the 0% PC + 6% silkworm pupae meal diet. Therefore, according to the authors, cheaper silkworm pupae meal could be an excellent substitute for the costly protein concentrate used to formulate diets for layers, which could lead to increased profitability.

*Turkeys (*Meleagris gallopavo *L.)*

Order Coleoptera (Beetles)

An experiment conducted by Despins and Axtell (1994) demonstrated that lesser mealworm (*Alphitobius diaperinus* Panzer) larvae can be used as selective feed for turkey poults. Insect meal was not used in this feeding trial. Instead, larvae were placed directly on the ground so the birds could freely forage for them. No significant difference was found between the body weight of poults that fed on larvae and starter feed compared to that of poults that fed on starter feed only.

On the contrary, the same authors (Despins and Axtell, 1995) used a similar design in a later study, and they reported that the body weight of chicks feeding on starter feed and larvae was significantly greater than the weight of chicks consuming feed only. Furthermore, these experiments showed that broiler chicks feed readily on darkling beetle larvae in the litter, and they consume large numbers during the first days of life.

Overview

From these studies using insects as food ingredient for poultry, we can draw the following conclusions:

- Although there are many studies, most are not comparable to each other. The diversity of insect species, insect breeding systems, varied control diets, number of chickens, environmental conditions, and so forth do not allow definitive conclusions to be drawn. Thus, larger scale and more systematic studies utilizing more standardized and industrially relevant methodologies are needed.
- Most of the experiments were conducted in developing countries. As noted by Khatun et al. (2003), a limited number of feed ingredients are available for the formulation of balanced diets. Moreover, fish meal (a conventional animal protein source) is scarce and expensive, and it may even contain lethal pesticides that are detrimental deleterious to the poultry industry (Khatun et al., 2003). Therefore, if we want to increase the profitability of poultry production in these countries, the search for unconventional feed ingredients is especially relevant.
- Native insect species in each area are often studied. Furthermore, some species have been traditionally consumed by humans (Nigeria) or are by-products (eg, silkworm pupae), but have not been previously tested in broilers.
- The available literature confirms the feasibility of total or partial replacement of fish meal (fish meal) with insect meal (insect meal). The highest inclusion percentages were reported in some Orthoptera (up to 30 of the diet) (DeFoliart et al., 1982; Finke et al., 1985). Regarding house fly, most trials indicate that partial or even total replacement of fish meal is possible, although the optimal inclusion rate is generally lower than 10% (Makkar et al., 2014). Higher rates have resulted in lower intake and performance, which may be due to a decrease in palatability. For instance, the darker color of the meal may be less appealing to chickens (Atteh and Ologbenla, 1993; Bamgbose, 1999).
- Several studies analyzed economic valuation. Dutta et al. (2012), Khatun et al. (2003, 2005), Ijaiya and Eko (2009), and Sheikh and Sapcota (2007) estimated that increased benefits are obtained by replacing the fish meal or protein concentrate with silkworm pupae in poultry production. Therefore, silkworm meal could be a good substitute for scarce and expensive fish meal in broiler diets, which could increase economic gains (Ijaiya and Eko, 2009). Similarly, from an economic point of view, Akpodiete and Inoni (2000), Awoniyi et al. (2003), and Téguia et al. (2002) concluded that maggot meal could replace fish meal or maize (Adesina et al., 2011). Furthermore, it has no negative effect on the performance of the birds. According to Atteh and Ologbenla (1993), the cost of maggot harvesting and processing was about 83.3% lower than the costs associated with an equivalent weight of fish meal.

Pigs (*Sus* sp.)

There is limited information on the use of insects in pig feeding, but the results of a few tested species are promising. The use of silkworm pupae has been examined in growing and/or finishing pigs. The replacement of 100% soymeal (Coll et al., 1992) or fish meal (Medhi, 2011; Dankwa et al., 2000; Medhi et al., 2009a,b) with nondefatted silkworm meal resulted in no adverse effects on growth performance and carcass characteristics. However, at substitution levels higher than 50%, there was a reduction in intake, and it was compensated by a better FCR that did not alter carcass quality, meat quality, or blood parameters (Coll et al., 1992).

Regarding breeding pigs, only data for Diptera (specifically house fly and black soldier fly) are available. These studies indicate that the administration of insects in pig feed does not have adverse effects on reproduction. The sows and their offspring were fed a diet containing processed house fly meal (maggot meal), and there were no adverse effects on piglet performance, health (Bayandina, 1979; Bayandina and Inkina, 1980; Poluektova et al., 1980), or organoleptic properties or on the physiology and breeding performance of the sows (Bayandina and Inkina, 1980).

Supplementation with 10% house fly meal did not have a negative effect on body weight gain or FCE (Viroje and Malin, 1989), and the complete replacement of fish meal with house fly did not compromise growth performance or weaner pig economics (Dankwa et al., 2000).

Black soldier fly is especially valuable for pig feeding because of its lipid and calcium content, and it was as palatable to pigs as a soybean meal-based diet. However, it is deficient in methionine, cysteine, and threonine, and has high ash content (Newton et al., 1977). Black soldier fly prepupae meal allowed a 50% replacement of dried plasma in diets of early-weaned pigs, which resulted in increased weight gain and feed efficiency (Newton et al., 2005).

Fish

Fish are cultured animals that need high protein qualities and quantities. Aquaculture feeding is dependent on fish meal because of its particular nutritive characteristics. This dependence on fish meal and the high need for fish protein makes finding protein sources for fish meal replacement particularly important, and insects are good candidates. A sign of this interest is evident in the number of fish feeding trials using insects that has increased since the early century, and the increasing numbers seen in recent years are presented in Fig. 10.1.

Family Bagridae (Bagrid Catfishes)

Pelteobagrus vachellii **Richardson**

A 6-week growth trial was conducted to compare the effects of dietary supplementation with house fly and soybean meal on the growth performance and antioxidant responses of *P. vachellii*. The results showed that the 71% fish meal replacement reduced the growth rates and antioxidant capacity in both the house fly and soybean meal supplementation trials compared to a control diet (Dong et al., 2013).

Family Cichlidae (Cichlids)

Nile Tilapia (Oreochromis niloticus L.)

Order Coleoptera (Beetles)

Asiatic Rhinoceros Beetle (Oryctes rhinoceros L.). The results of experiments in Nile tilapia with Asiatic rhinoceros beetle culture under laboratory conditions did not seem to give promising results. The 16% fish meal substitution decreased the weight and survival. However, a negligible weight increase was also observed in the controls (2 g in 10 weeks) (Omoyinmi and Olaoye, 2012), which could be due to poor-quality fish meal in the diets used (35% protein), stress conditions, and/or fish disease (Henry et al., 2015).

Yellow Mealworm (T. molitor L.). The partial (25–50%) or total fish meal substitution of soybean meal with yellow mealworm larvae meal was examined. The results indicated that it did not affect the intake levels in fish, biometric indices, or the balance of essential and nonessential amino acids in fish muscle. However, the inclusion of yellow mealworm meal at any of the tested levels decreased the growth of Nile tilapia, worsened nutritional parameters, and affected the lipid profile of the fish muscle (Sánchez-Muros et al., 2015). The authors related the worse nutritive indices to the chitin content, which represents 1.4 and 2.8% for 25 and 50% fish meal substitutions in feeds, respectively. Moreover, the administration of a yellow mealworm larvae meal-based diet at early ages of development (with 25% fish meal substitution) did not cause irreversible effects on zootechnical parameters and biometric indices in Nile tilapia. Additionally, these parameters could recover when they were subsequently provided with a control diet (without insect meal), and the same was true for high unsaturated fatty acid (HUFA) muscle composition, which was altered by ingestion of the insect-based diet (de Haro, 2015).

Superworm (Zophobas morio Fab.). Utilizing superworm as a fish feed suppliment, Jabir et al. (2012b) achieved a 50% replacement of fish meal with superworm in Nile tilapia diets that resulted in optimal growth. Moreover, even a 75% replacement was well tolerated in terms of growth, FCE, and protein digestibility. Nevertheless, the apparent digestibility coefficients of protein and lipids were less for superworm meal than fish meal, and this was reflected in low lipid percentages found in muscles at all substitution levels tested as compared to the fish fed fish meal. This result occurred despite the major lipid content in diets formulated with superworm. Therefore, the authors suggested that slight improvements to the superworm containing fish diets are necessary before they can entirely replace fish meal as feed for Nile tilapia (Jabir et al., 2012a).

Order Diptera (Flies)

House Fly (M. domestica). The substitution percentage of house fly in place of fish meal has been established at 50% (Ajani et al., 2004) and 34% (Ogunji et al., 2007, 2008a,b,c). Nevertheless, a resulting weight gain similar to fish meal-fed fish is possible with a 100% substitution (Ajani et al., 2004; Ogunji et al., 2007, 2008b,c). Moreover, results suggest that feeding Nile tilapia fingerlings maggot meal diets did not cause physiological stress (Ogunji et al., 2007), but did affect the fatty acid profile in fish. Therefore, adequate sources of n-6 and n-3 fatty acids should be included in the diet (Ogunji et al., 2008b).

On the other hand, the substitution percentage seemed dependent on the minimum fish meal levels. Nile tilapia growth decreased significantly compared to that of the control groups when fish meal was reduced by 17.31% in the feed, and when 15% house fly was subsequently introduced. The results indicated that the protein efficiency ratio was not affected, although the inclusions were even higher (Ogunji et al., 2008c). This may be related to the composition and the dietary protein/energy ratio of the different diets. In addition, with higher substitutions, the apparent digestibility of crude protein worsened in Nile tilapia, and this was probably due to higher ash content in the diet (Ogunji et al., 2008c).

The combination of wheat bran and live house fly added to Nile tilapia feed has also been studied. At a 4:1 ratio of wheat bran: live house fly, the results showed better growth performance, specific growth rate, FCR, and survival than when wheat offal was fed singly (Ebenso and Udo, 2003). The results also revealed that diets with house fly protein were as effective in terms of growth and survival as fish meal for that species (Ogunji et al., 2007, 2008a,b,c; Omoyinmi and Olaoye 2012).

Order Orthoptera (Crickets, Grasshoppers, Locusts, and Katydids)

Migratory Locust (L. migratoria) The replacement of fish meal with migratory locust meal in Nile tilapia fingerling diets showed that 25, 50, and 75% substitutions were not significantly different from the control diet regarding protein digestibility. Furthermore, 25 and 50% substitutions did not differ significantly in lipid digestibility compared to the control. However, considering growth performance and hematological parameters, migratory locust meal could replace fish meal up to 25% without any adverse effects on growth performance and hematological parameters (Abanikannda, 2012; Emehinaiye, 2012 in Makkar et al., 2014).

Order Lepidoptera (Butterflies, Moths, and Their Caterpillar Larval and Chrystalis/Pupal Stages)

Defatted and nondefatted *silkworm* meal led to very good digestibility values in Nile tilapia (Hossain et al., 1992; Boscolo et al., 2001). However, a low inclusion level (5%) significantly reduced fish growth compared to fish meal-fed fish in control diets formulated with 5% fish meal (Boscolo et al., 2001).

Family Clariidae (Airbreathing Catfishes)

African Catfish (*Heterobranchus bidorsalis* Geoffroy Saint-Hilaire)

Order Isoptera (Termites; Macrotermes nigeriensis) Solomon et al. (2007) conducted a trial with African catfish fingerlings fed fish meal-based diets supplemented with *M. nigeriensis* and soybean meal at different ratios for 56 days. They found better growth performance and nutrient utilization when *M. nigeriensis* was included in the blend at a 75:25 ratio (*M. nigeriensis*: soybean meal). However, the variation in soybean meal and fish meal between the experimental diets made it difficult to establish whether the improved fish growth was due to dietary insects or to the increased dietary fish meal. On the other hand, there were marked significant differences in the ash, lipid, and crude protein of the carcasses of fish fed the different experimental diets (Solomon et al., 2007).

*African Sharptooth Catfish (*Clarias gariepinus *Burchell)*

Order Coleoptera (Beetles)

Yellow Mealworm (T. molitor) Yellow mealworm, whether used unaltered or transformed into a dry meal, is an acceptable alternative protein source that is highly palatable for African sharptooth catfish (Ng et al., 2001). During a 7-week feeding trial, Ng et al. (2001) showed that yellow mealworm could replace up to 40% fish meal without affecting growth performance and feed utilization efficiency. Diets with up to 80% replacement of fish meal with yellow mealworm still displayed good growth and feed utilization efficiency, but the values were lower than fish fed the control diet. Feeding solely with mealworms displayed a slight depression in growth performance, but when fed in combination with commercial pellets, African sharptooth catfish grew better than those fed the commercial pellets only (Ng et al., 2001). Regarding body composition, the ingestion of yellow mealworm significantly increased the lipids in the carcass (Ng et al., 2001).

Order Diptera (Flies)

House Fly (M. domestica) The results of house fly studies as feed ingredient for African sharptooth catfish are contradictory. In an 8-week study, house fly meal was detrimental to the growth performance at all levels of diet inclusion (12.5%, 50%, and particularly at 100%). However, nutrient utilization was less affected, and the best FCR and PER results were found in diets with 25 and 50% inclusion, respectively (Idowu et al., 2003). In contrast, African sharptooth catfish fed diets with 50 or 100% fish meal replacement with house fly meal for 10 weeks grew well (Nsofor et al., 2008; Aniebo et al., 2009). Oyelese (2007) found that African sharptooth catfish fed 50% live house fly in conjunction with a 50% artificial diet that was poor in fish meal (3.5%) grew better than fish fed the artificial diet alone over the 7-week experimental period. Moreover, no differences in organoleptic properties were found in African sharptooth catfish fed house fly meal (Aniebo et al., 2011). Therefore, it has been concluded that house fly meal is a viable alternative protein source to fish meal in the diet of African sharptooth catfish, (Aniebo et al., 2009; Oyelese, 2007).

On the other hand, the combination of hydrolyzed chicken feather meal, chicken offal meal, and house fly meal at a ratio of 4:3:2 as alternative animal protein mixture was also evaluated as a replacement for fish meal in African sharptooth catfish fingerling diets. The results indicated no significant differences in weight gain, specific growth rate, FCR, or protein efficiency ratio in fish fed the diet with 25–50% substitution and those fed the control diet (Adewolu et al., 2010).

In one study, processing methods, such as defatting and drying, influenced the nutrient concentration of house fly meal. However, the growth performance and nutrient utilization of African sharptooth catfish fed a diet with 100% fish meal replaced with defatted, oven dried and defatted, sun-dried maggot meals were not significantly different from each other, and the parameters were similar to those obtained in fish fed the fish meal-based diet. Generally, African sharptooth catfish performed better when fed diets containing defatted maggot meals than full-fat maggot meals, and this compared favorably with fish fed the fish meal-based diet (Fasakin et al., 2003).

Order Orthoptera (Crickets, Grasshoppers, Locusts, and Katydids)

Desert Locust (Schistocerca gregaria Forsskål) This insect is famous for its vast seasonal swarms which can ravage most plants in their path across Africa, the Middle East, and Asia. It is best known for devastating crops in Africa over many centuries and mentioned in the Bible as an agricultural plague even in that time. It remains an extremely abundant insect and an important agricultural pest today. For its utility as a livestock feed, one study to date has demonstrated that the replacement of up to 25% fish meal with desert locust in African sharptooth catfish juvenile diets did not affect growth (Balogun, 2011).

Variegated Grasshopper (Zonocerus variegatus L.) Using an 8-week trial, Alegbeleye et al. (2012) showed that adult variegated grasshopper meal could replace up to 25% of the fish meal in African sharptooth catfish fingerling diets without any adverse effects on growth and nutrient utilization. The results indicated increases in the inclusion level, performance, and carcass lipids, and decreases in apparent protein and lipid digestibility were observed. No statistical differences in the FCR and protein efficiency ratio were detected.

Mudfish (*Clarias anguillaris* L.)

Order Diptera (Flies)

House Fly (M. domestica). The use of frozen or live house fly larvae (maggot meal) to supplement artificial diets has been recommended for mudfish production, because it promoted fast growth rates in the fingerlings than did commercial feed (Achionye-Nzeh and Ngwudo, 2003; Madu and Ufodike, 2003). Mudfish juveniles fed unconventional diets exhibited the greatest increase in body weight, specific growth rate, and condition factors when fish were fed the commercial diet supplemented with live house fly, followed by an exclusive house fly diet (Madu and Ufodike, 2003). The combination of house fly and the commercial diet might have formed a better balanced diet for juvenile mudfish (Madu and Ufodike, 2003).

Order Isoptera (Termites)

M. nigeriensis. The growth response of mudfish fingerlings fed diets formulated with 10–40% *M. nigeriensis* Sjostedt without fish meal for 42 days showed that the growth rate of fish increased with increased protein content of the feed. The best daily weight gain and total weight gain were observed in fish fed a diet with 40% *M. nigeriensis* (Achionye-Nzeh et al., 2004).

Vundu (*Heterobranchus longifilis* Valienciennes)

Order Diptera (Flies)

House Fly (M. domestica). Comparisons between soymeal, cattle brain meal, and house fly meal included at 80% showed that house fly meal supplemented with amino acids results in better performance in vundu than soymeal. Moreover, these conditions resulted in lower performance than fish that were fed cattle brain meal during a 7-week feeding trial (Ossey et al., 2012), but no fish meal control diet was used to compare results.

Order Isoptera (Termites)

Macrotermes sp. In a 12-week experiment focusing on *Macrotermes* sp. meal as substitute for fish meal diets (0–100%), Sogbesan and Ugwumba (2008) used broken-line analysis and found that 50% inclusion levels of *Macrotermes* sp. meal yielded the best results. For instance, fish fed this diet exhibited the highest mean weight gain, relative growth rate, specific growth rate, and protein efficiency ratios as well as the lowest FCRs.

Walking Catfish (*Clarias batrachus* L.)

Order Lepidoptera (Butterflies, Moths, and Their Caterpillar Larval and Chrystalis/Pupal Stages) Silkworm pupae meal was found to be a suitable fish meal substitute in walking catfish diets (Venkatesh et al., 1986; Borthakur and Sarma, 1998a,b). The results indicated that walking catfish fed silkworm meal had slightly lower specific growth rates, minor protein efficiency ratios, and poorer FCRs than fish fed fish meal diets. However, the digestibility of crude protein (Borthakur and Sarma, 1998a) and intestinal protease activity (Venkatesh et al., 1986) were similar to fish fed fish meal diets.

Order Orthoptera (Crickets, Grasshoppers, Locusts, and Katydids) Although research suggests the suitability of utilizing the grasshopper *Poekilocerus pictus* (Fab.) as a partial substitute for fish meal in formulated walking catfish diets, results of studies using this insect have not been promising; the fish feed with grasshopper (Johri et al., 2010; Johri et al., 2011b) grew lower than fish feed fish meal diets. The 100% substitution of fish meal in a 91-day trial had no effect on hematological parameters. However, minor shrinkage of the gills was observed in fish fed with grasshopper diet and a reduction in ovarian steroidogenesis was noted, which may be associated with reduced fertility (Johri et al., 2011a,c).

Family Cyprinidae (Carps and Minnows)

Black Carp (*Mylopharyngodon piceus* Richardson)

Order Diptera (Flies)

House Fly (M. domestica). Supplementation with 25 g/kg house fly meal promoted growth in black carp, which improved weight gain and specific growth rates without changes in muscle composition. The growth enhancement seemed to result from an improvement in immunological status (Ming et al., 2013).

Common Carp (*Cyprinus carpio* L.)

Order Lepidoptera (Butterflies, Moths, and Their Caterpillar Larval and Chrystalis/Pupal Stages)

Silkworm/Silkmoth (B. mori). Nondefatted *silkworm* pupae meal could replace fish meal in the diet of common carp (Jeyachandran and Raj, 1976; Nandeesha et al., 1990, 2000) without affecting growth performance, FCE, and quality in terms of color, odor, texture, and flavor (Nandeesha et al., 1990, 2000).

Defatted silkworm pupae were less digestible than fish meal (Kim, 1974), and the protein and fat digestibility of nondefatted silkworm pupae were better than that of fish meal. This difference is due to higher protease enzyme activity and a significantly higher deposition of protein in fish fed defatted insect diets (Nandeesha et al., 1990, 2000). However, a 100% substitution of fish meal with defatted silkworm pupa could be utilized (Kim, 1974). Finally, the usefulness of silkworm pupa oil as an energy source in comparison to sardine oil for common carp has been examined with acceptable results (Nandeesha et al., 1999).

Deccan Mahseer (*Tor khudree* Sykes)

The use of silkworm as feed was examined in Deccan mahseer fingerlings with promising results. Better growth and survival were obtained in fish fed a diet containing 50% defatted silkworm pupae (Shyama and Keshavanath, 1993 in Makkar et al., 2014).

Prussian Carp (*Carassius gibelio* Bloch)

Order Diptera (Flies)

House Fly (M. domestica). A 6-week growth trial was conducted to investigate the effects of dietary supplementation with house fly and soybean meal (with a 71% fish meal substitution in the control diet) on the growth performance and antioxidant responses of Prussian carp. The results indicated a significant decrease in the specific growth rate in fish fed the soybean meal diet compared to those fed the control diet (Dong et al., 2013).

Putitor Mahseer (*Tor putitora* Hamilton)

Order Lepidoptera (Butterflies, Moths, and Their Caterpillar Larval and Chrystalis/Pupal Stages) An experiment was conducted to study the growth performance of Putitor Mahseer fingerlings fed during a 60-day trial, and the results indicated that acceptable growth was observed in fish feed a diet with a 70% substitution of fish meal with silkworm pupae (Sawhney, 2014).

Rohu (*Labeo rohita* Hamilton)

Order Lepidoptera (Butterflies, Moths, and Their Caterpillar Larval and Chrystalis/Pupal Stages)

Silkworm/Silkmoth (B. mori). A 90-day experiment that focused on the effects of a diet with a 50% replacement of fish meal with silkworm pupae and clam meat on rohu fingerlings revealed a significantly better utilization of the experimental diet (Begun et al., 1994).

Regarding the processing of the meal, silkworm that did not undergo the deffating process were better than defatted silkworm, but the differences were not significant (Hossain et al., 1997). Nevertheless, both silkworm and defatted silkworm pupae that were used as the sole source of protein produce significantly better apparent and true protein digestibility values than those fed the fish meal diet (Hossain et al., 1997).

Silver Barb (*Barbonymus gonionotus* Bleeker)

Order (Butterflies, Moths, and Their Caterpillar Larval and Chrystalis/Pupal Stages)

Silkworm/Silkmoth (B. mori). In silver barb fingerlings, the substitution of fish meal with silkworm pupae was examined. The highest growth rate, FCR, protein efficiency ratio, apparent net protein utilization, apparent protein digestibility, and growth performance were observed in fish fed a diet in which about 38% of the total dietary protein was replaced silkworm pupae meal. However, the diet containing lower levels of silkworm pupae (19.1%) and higher levels of mustard oilcake (19.8%) led to reduced fish growth. Economic analyses of the diets suggested the possibility of using silkworm pupae as an alternative source of protein in silver barb feed (Mahata et al., 1994).

Family Heteropneustidae (Airsac Catfishes)

Stinging Catfish (*Heteropneustes fossilis* Bloch)

Order Lepidoptera (Butterflies, Moths, and Their Caterpillar Larval and Chrystalis/Pupal Stages)

Silkworm/Silkmoth (B. mori). Researchers managed to successfully achieve a 75% substitution of fish meal with silkworm pupae meal in stinging catfish diets without adverse effect on growth (Hossain et al., 1993 in Makkar et al., 2014).

Family Ictaluridae (Freshwater Catfishes)

Black Bullhead (*Ameiurus melas* Rafinesque)

Order Coleoptera (Beetles)

Yellow Mealworm (T. molitor). In a 90-day trial, the 50% substitution of fish meal with yellow mealworm meal showed good growth performance in black bullhead. However, fish in the insect meal group reached a final mean body weight that was significantly lower than that of the fish meal group, and the survival rate of the fish meal group was significantly higher (Roncarati et al., 2014). Fish in the fish meal group were fed a control diet (51.6% protein and 18.1% lipid), whereas those in the insect meal group received an experimental diet (50.8% protein and 22.1% lipid). However, the differences in the macronutrient contents of the diets could have affected the results.

Channel Catfish (*Ictalurus punctatus* Rafinesque)

Order Diptera (Flies)

Black Soldier Fly (H. illucens). The level of positive results for replacement of fish meal with black soldier fly depends on the culture system. For example, the replacement of 10% fish meal with 10% dried black soldier fly prepupae (whole or chopped and reared on poultry manure) over a 15-week period for subadult channel catfish grown in cages resulted in slower growth rates (weight gain and total body weight) and decreased animal crude protein content. In contrast, if channel catfish was cultured in tanks at a slower growth rate, the replacement did not significantly reduce the growth rate (Bondari and Sheppard, 1987).

Regarding the administration method, results have indicated increased uneaten larval waste in the chopped larvae fed tanks compared to those in the whole larvae fed tanks. However, chopping improved weight gain and efficient utilization by the fish (Bondari and Sheppard, 1987).

Comparison between menhaden fish meal and prepupae black soldier fly meal showed that 25% fish meal replacement was possible without compromising weight gain. Moreover, a 100% replacement was possible if the diets were supplemented with soybean meal in order to obtain isoproteic diets (Newton et al., 2005). More recently, Zhang et al. (2014) found that the replacement of 25% fish meal with chicken manure conversion with microorganisms and black soldier fly larvae powder resulted in similar growth indices, immunity indices, and bodies compared to the control group. However, higher substitutions did not produce satisfactory results.

Family Lateolabracidae (Ray-Finned Fish)

Japanese Seabass (*Lateolabrax japonicus* Cuvier)

Order Lepidoptera (Butterflies, Moths, and Their Caterpillar Larval and Chrystalis/Pupal Stages)

Silkworm/Silkmoth (B. mori). In Japanese seabass that were fed a combination of commercial feed and various food sources at a 70:30 ratio, the energy and protein apparent digestibility coefficient of silkworm pupae that were not defatted was lower than poultry by-product meal, blood meal, and soybean meal. However, it was comparable to that of feather meal (Ji et al., 2010).

Family Moronidae (Temperate Basses)

European Seabass (*Dicentrarchus labrax* L.)

Order Coleoptera (Beetles)

Yellow Mealworm (T. molitor). The effects of yellow mealworm inclusion on the growth and feed efficiency of European seabass juveniles were studied by Gasco et al. (2014b), with a 25% substitution satisfactorily achieved. However, at a 50% substitution, yellow mealworm induced growth reduction and less favorable outcomes for both the specific growth rate and feed consumption ratio. The protein efficiency ratio and feed consumption were not affected by the inclusion of yellow mealworm, and the whole body proximate composition analysis did not show any differences between the treatments. On the other hand, yellow mealworm inclusion influenced the fatty acid composition of body lipids. In particular, a decrease in the contents of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) was observed with an increase to a 50% inclusion of yellow mealworm meal.

Family Osphronemidae (Giant Gouramis)

Snakeskin Gourami (*Trichogaster pectoralis* Regan)

Order Lepidoptera (Butterflies, Moths, and Their Caterpillar Larval and Chrystalis/Pupal Stages)

Silkworm/Silkmoth (B. mori). Jintasatapom et al. (2011) showed that silkworm could replace 50% of the protein from fish meal in snakeskin gourami broodstock diets without any adverse effects on egg quality (in terms of fry number from the first spawn and fingerling number). However, growth performance and egg fecundity were significantly decreased with the increased percentage of silkworm pupae in the diet. The results indicated that protein digestibility decreased according to the inclusion level of silkworm pupae in the diets. In contrast, the dry matter digestibility was similar to the control, and egg quality (in terms of fry number and fingerling number of the first spawn) was not significantly different ($P > 0.05$). The survival rate of 1-month nursing fish of the first spawn was significantly different ($P < 0.05$) at the 100% substitution. Hence, a 50% protein substitution of fish meal with silkworm pupae (14.57% by weight) could be used in snakeskin gourami broodstock diets without any adverse effects on egg quality.

Family Paralichthyidae (Sand Flounders)

Bastard Halibut (*Paralichthys olivaceus* Temminck and Schiegel)

According to a study by Lee et al. (2012), silkworm can replace 10% fish meal in bastard halibut diets. The replacements of fish meal with 10 and 20% silkworm pupae meal was tested in bastard halibut diets, and the best performance was achieved with the 10% silkworm pupae meal replacement, as compared to the control diet (Lee et al., 2012).

Family Salmonidae (trouts and Salmons)

Atlantic Salmon (*Salmo salar* L.)

Lock et al. (2014) tested the replacement of fish meal with black soldier fly larva meal (0, 25, 50, and 100%) in Atlantic salmon. The feed intake and FCR decreased with increasing black soldier fly inclusion, which increased the utilization of feed for growth. The protein and lipid digestibility, histology, and sensory testing of fillets did not show any differences among the treatments. The authors concluded that a favorable amino acid profile and high medium-chain fatty acid content are needed to make black soldier fly meal a promising ingredient for use in Atlantic salmon diets.

The nutrient isolation and processing methods of the insect meal have an important impact on the performance of the product. For instance, highly defatted black soldier fly meal that was dried at a conventional temperature resulted in low growth in fish compared to those fed lightly defatted black soldier fly meal that was dried at a low temperature. Moreover, the lightly defatted black soldier fly meal allowed a 100% substitution of fish meal, which had similar growth indices compared to fish fed the control diet (Henry et al., 2015).

Chum Salmon (*Oncorhynchus keta* Walbaum)

Order Lepidoptera (Butterflies, Moths, and Their Caterpillar Larval and Chrystalis/Pupal Stages)

Silkworm/Silkmoth (B. mori). In a 6-week feeding experiment with chum salmon fry, Akiyama et al. (1984) evaluated the replacement of fish meal with silkworm preferentially over other ingredients, but they did not obtain results better for insect meal over fish meal or any other protein meals. Fish were fed fish meal diets or diets supplemented with silkworm pupae powder (5%), dried beef liver (5%), krill meal (5%), or earthworm powder (5%) in place of fish meal. None of the dietary treatments appreciably increased the food intake of the fish over that of the control group, and no significant differences were noted in body protein and ash contents among all dietary treatments (Akiyama et al., 1984).

Rainbow Trout (*Oncorhynchus mykiss* Walbaum)

Order Coleoptera (Beetles)

Yellow Mealworm (T. molitor). Gasco et al. (2014a) reached an inclusion level of up to 50% yellow mealworm without a growth performance reduction in rainbow trout feedstuffs. In a 75-day feeding trial, there were no statistical differences for 0, 25, or 50% fish meal replacements in growth performance metrics and proximate composition of the resulting fish. The lowest hepatosomatic indices were observed in fish fed the 25 and 50% yellow mealworm replacement diets.

Order Diptera (Flies)

Common House Mosquito (Culex pipiens L.). The common house mosquito has been evaluated as a feed for rainbow trout fed exclusively with frozen mosquitos, and the results showed a decrease in growth compared with fish given control supplemented with amino acids (dipeptide glycine-lysine or free glycine and free lysine) but higher than control diet without suppletetation of amino acids (Ostaszewska et al., 2011).

Black Soldier Fly (H. illucens). In a 9-week study, researchers replaced 0, 25, or 50% of the fish meal protein in juvenile rainbow trout diets with black soldier fly prepupae meal (reared on swine manure). Compared to the control, no differences in total weight gain and feed conversion of fish fed at 25% were observed (St-Hilaire et al., 2007b). The protein content of fish after the end of the experiment did not differ significantly between treatments, and the lipid content was less in fish fed with black soldier fly at any level. Moreover, the inclusion of black soldier fly pupae in fish feed altered the fatty acid profile of rainbow trout, in that fish fed black soldier fly diets were low in fish oil had low levels of Omega-3 fatty acids in muscle (St-Hilaire et al., 2007b). Nevertheless, the fatty acid profile of insects could be modified by feeding methods that allow increased fish meal replacement, which could restore the levels of n-3 in fish muscle (Sealey et al., 2011).

House Fly (M. domestica). During a 9-week feeding trial, St-Hilaire et al. (2007a) evaluated the inclusion of 25% house fly meal (reared on cow manure) in place of fish meal in rainbow trout diets. In contrast to the results described for black soldier fly, the total weight gain was less for fish fed the 25% house fly diet compared to the control. However, compared to the controls, no differences were observed in the FCR, protein and lipid content, muscle fatty acid profile for linoleic acid, EPA, DHA, or ARA contents of the whole-body proximate composition.

Order Lepidoptera (Butterflies, Moths, and Their Caterpillar Larval and Chrystalis/Pupal Stages) Silkworm pupae have been examined as a shrimp meal substitute in rainbow trout. A 100% replacement of shrimp meal indicated a significantly higher specific growth rate compared to fish fed a control diet (Dheke and Gubhaju, 2013).

Family Scophthalmidae (Turbots)

Turbot (*Psetta maxima* L.)

Kroeckel et al. (2012) showed that the incorporation of black soldier fly protein in juvenile turbot diets is possible, but it is limited to a 33% inclusion to avoid significant changes in feed intake, feed conversion, and protein retention. However, both indices, feed intake and specific growth rate, decreased with increasing black soldier fly incorporation, and this was likely due to the palatability and low apparent digestibility coefficients of organic matter, crude protein, crude lipid, and gross energy. Regarding body composition, the whole-body protein content was not affected by the treatment, but body lipid content decreased with increasing black soldier fly inclusion levels.

Family Sparidae (Porgies, Sea Breams)

Gilt-Head Bream (*Sparus aurata* L.)

Order Coleoptera (Beetles) The substitution of fish meal with up to 25% yellow mealworm protein in gilt-head bream juvenile diets is feasible without adverse effects on growth performance and whole-body proximate composition (Piccolo et al., 2014). However, a slight depression was observed in the protein efficiency ratio and the FCR during a 60-day trial. Furthermore, the 50% substitution induced less favorable indices (Piccolo et al., 2014).

Order Diptera (Flies)

Common Green Bottle Fly (Lucilia sericata Meigen). Gilt-head bream fed during a 33-day trial with different substitution percentages (0, 25, and 50%) of fish meal with common green bottle fly larvae meal (cultured with pork liver) resulted in a final weight that was similar to fish fed the control diet (without common green bottle fly). Furthermore, with respect to body composition, the only significant difference was observed for regarding the muscle lipid percentage of fish fed the maximum replacement (de Haro et al., 2015).

Hybrid Fish

*Vundu (*H. longifilis*) × African Sharptooth Catfish (*C. gariepinus*)*

Order Diptera (Flies)

House Fly (M. domestica) The study of growth responses, FCRs, and cost benefits of hybrid catfish vundu × African sharptooth catfish fed different substitution percentages of fish meal with house fly maggots meal (0–100%) showed that a 25% substitution had the best growth performance and the highest mean growth rate. However, no significant differences were observed on specific growth rate (SGR) and final weight for diets at 0, 50, and 75% replacements of fish meal (Sogbesan et al., 2006).

Polyculture

*Major Indian Carp (*Catla catla *Hamilton), Mrigal Carp (*Cirrhinus mrigala *Bloch), Rohu (*L. rohita*), and Silver Carp (*Hypophthalmichthys molitrix *Valenciennes)*

Order Lepidoptera (Butterflies, Moths, and Their Caterpillar Larval and Chrystalis/Pupal Stages)

Silkworm/Silkmoth (B. mori) Silkworm has been studied as feed ican a polyculture system consisting of 30% major Indian carp, mrigal carp, rohu and 10% silver carp. Silkworm treatment was evaluated for silkworm pupae silage and untreated fresh pastes that were incorporated in fish feed formulations to replace fish meal. The results clearly indicated that the survival rate, FCR, and specific growth rate with fermented silkworm pupae silage were nutritionally superior to untreated silkworm pupae silage or fish meal. The dietary influence on the proximate composition of whole fish was marginal (Rangacharyulu et al., 2003).

*African Sharptooth Catfish (*C. gariepinus*) and Vundu (*H. longifilis*)*

Order Coleoptera (Beetles)

Asiatic Rhinoceros Beetle (O. rhinoceros L.) Asiatic rhinoceros beetle can be used to completely replace fish meal in fish diets in mix cultures of African sharptooth catfish and vundu. However, for optimal growth and nutrient utilization, a 25% level of fish meal replacement with Asiatic rhinoceros beetle meal is most suitable for the fingerlings of both fish species. The study also showed that Asiatic rhinoceros beetle meal is more suitable for African sharptooth catfish than vundu (Fakayode and Ugwumba, 2013).

*Common Carp (*C. carpio*) and Nile Tilapia (*Oreochromis niloticus*)*

Order Diptera (Flies)

House Fly (M. domestica) The digestibility of house fly compared to a reference diet (fish meal as a primary protein source) and a test diet (70% reference diet + 30% house fly meal) was evaluated in Nile tilapia and common carp. The apparent digestibility coefficients for dry matter, crude protein, crude fat, and gross energy of house fly were significantly lower for Nile tilapia than for common carp. However, the spawning activities of experimental Nile tilapia and the soft feces consistency of common carp may have affected the results (Ogunji et al., 2009).

*Channel Catfish (*I. punctatus*) and Blue Tilapia (*Oreochromis aureus *Steindachner)*

Order Diptera (Flies)

Black Soldier Fly (H. illucens) The substitution of a commercial diet with 50 or 75% black soldier fly larvae was tested during a 10-week trial for the polyculture of channel catfish and blue tilapia, and the results indicated that fish body weight and total length were not affected. Moreover, the taste test results regarding the aroma and texture of fish fed black soldier fly larvae were acceptable to the consumer (Bondari and Sheppard, 1981).

*Chinese White Shrimp (*Fenneropenaeus chinensis *Osbeck) and Japanese Blue Crabs (*Portunus trituberculatus *Miers)*

Order Diptera (Flies)

House Fly (M. domestica) In a polyculture of Chinese white shrimp and Japanese blue crabs that were fed a diet containing 30–50% housefly maggot meal, the yields and survival of the shrimp and crabs were higher than those fed control diets. Furthermore, shrimp and crabs fed the MGM diet had significantly higher body weight, especially in the mid- and late-culture periods (Zheng et al., 2010a).

Crustaceans (Shrimp, Crabs, Lobsters and Their Relatives)

Family Palaemonidae

Giant River Prawn (*Macrobrachium rosenbergii* De Man)

Feces from black soldier fly larvae (reared on dried distiller's grains) were used in commercial prawn farms to replace the regular commercial feed. The results showed a performance similar to that of the regular giant river prawn feed, and the economic returns were enhanced. The only notable difference was that the prawns fed the black soldier fly feces diet were slightly more pale than those fed the traditional diet, but there were no changes in flavor (Tiu, 2012).

Family Penaeidae (Penaeid Shrimps)

Chinese White Shrimp (*F. chinensis* Osbeck)

Juvenile Chinese white shrimp fed diets containing different proportions of house fly exhibited enhanced body length, body weight, specific growth rate, and survival, which corresponded with increased dietary house fly. On the other hand, the total n-3 HUFA and n-6 HUFA in the shrimp muscles increased with increased house fly proportions in the diets. However, the essential fatty acid content and higher polyunsaturated fatty acids in the muscles of shrimp fed house fly were significantly lower than those of the shrimp in the control group (Zheng et al., 2010a,b).

Speckled Shrimp (*Metapenaeus monoceros* Fab.)

Order Lepidoptera (Butterflies, Moths, and Their Caterpillar Larval and Chrystalis/Pupal Stages)

Silkworm/Silkmoth (B. mori). Shrimp growth trials showed that digestive efficiency was reduced when silkworm meal replaced fish meal (Sumitra-Vijayaraghavan Wafar and Royan, 1978 in Makkar et al., 2014)

Whiteleg Shrimp (*Litopenaeus vannamei* Boone)

According to growth performance parameters, antioxidant indices, and nonspecific immune indices of juvenile whiteleg shrimp, the best replacement ratio of fish meal with house fly meal was 40%, and the maximum level should not exceed 60% (Cao et al., 2012a). Specific growth rate tended to decrease with house fly inclusion, and the muscle nutritional composition showed a positive correlation between the crude protein and ash content of the muscle and the proportion of house fly meal in the diet. The crude protein content at a 100% substitution and the ash content at 80 and 100% replacements were significantly higher than that of the control group, and no effects on moisture and crude lipid content were observed. No significant effects on the nutritional composition, essential amino acid, delicious amino acid, or inosine monophosphate content in the muscle were observed. However, the arginine content increased with increasing fish meal substitution increments. Digestive enzymes were also studied, and no effects on activity associated with house fly inclusion were observed. However, pathological changes in the histological structure of the hepatopancreas were observed with replacement levels over 60% (Cao et al., 2012b).

Mollusks (Clams, Oysters, Snails and Their Relatives)

*Disk Abalone (*Haliotis discus *Reeve)*

Order Lepidoptera (Butterflies, Moths, and Their Caterpillar Larval and Chrystalis/Pupal Stages)

Silkworm/Silkmoth (B. mori) Cho (2010) studied the growth and survival of disk abalone juveniles that were fed the following diets: control, soybean meal, poultry meal, corn gluten meal, dehydrated silkworm pupae meal, meat and bone meal, soybean meal and corn gluten meal, soybean meal and dehydrated silkworm pupae meal, and corn gluten meal and dehydrated silkworm pupae meal. The combined soybean meal and corn gluten meal or the silkworm pupae meal and soy meal could completely replace fish meal in the abalone diet, resulting in improved performance.

Overview

It is difficult to obtain clear conclusions because of the variety of fish and insects species examined in studies of diet formulation, ingredients, and so forth. In general, the results showed that insects could play an important role in aquaculture feeding. Nevertheless, substantial knowledge is needed to successfully use insects as alternatives to fish meal. All of these studies indicate the need to expand upon the following key points:

- To determine the most adequate insects species for each fish species.
- To evaluate and develop various insect species and production methodologies which are most economical end practical as an animal feed commodity.
- To evaluate influence of insect meal on muscle quality.
- To study efficient administration techniques: chopped, whole, alive, and so on.
- To analyze the influence of culture systems on the nutritive utilization of insect-based diets.
- To assess the optimal fish meal substitution percentage.
- To test different strategies to improve the nutritive values of insect meals.

Other Animals

*American Alligator (*Alligator mississippiensis *Daudin)*

Order Diptera (Flies)

Black Soldier Fly (H. illucens) Black soldier fly larvae cannot be recommended as a complete replacement for commercial feed in young American alligators (Bodri and Cole, 2007). The feeding of American alligators with dried black soldier fly larvae (reared on restaurant food waste) reduced weight and increased the snout-vent length (Bodri and Cole, 2007).

*Giant Ditch Frog (*Leptodactylus fallax *Müller)*

Order Diptera (Flies)

Black Soldier Fly (H. illucens) Black soldier fly larvae had poor nutrient digestibility in giant ditch frogs. However, the digestibilities of almost all nutrients except Na and K were enhanced through processing (pureeing). After processing or chewing that broke the exoskeleton, black soldier fly larvae supplied high levels of dietary minerals without the need for additional external Ca. Moreover, Ca and P digestibilities were approximately two-fold higher than that for mashed larvae (about 90% versus 45–50%), and they were similar to values measured for supplemented cricket-based diets (Dierenfeld and King, 2008 in Makkar et al., 2014).

*Rat (*Rattus *sp.)*

Order Diptera (Flies)

House Fly (M. domestica) The feed value of dried house fly larva meal was compared in a nutritional study of growing rats (Bouafou et al., 2011a,b). The chemical composition of rats, feed intake and weight gain of subjects, feed and protein efficiency ratios, digestibility, net protein utilization, and biological value parameters were similar at 2.5, 5, and 7.5% inclusions of dried house fly meal. The regime at 5% inclusion had the best nutritional value (Bouafou et al., 2011b). Nevertheless, damage to kidney tissue and liver portal veins was found in rats fed dried house fly meal (Bouafou et al. 2011a,b).

BENEFITS AND CONSTRAINTS ASSOCIATED WITH USING INSECTS AS LIVESTOCK FEED INGREDIENTS

Nutritional

Source of Protein and Amino Acids

The use of insects in animal feed has been mainly focused on their value as a protein source. Studies of insect protein values indicated that most species had high protein quantities (Ladrón de Guevara et al., 1995; Ramos-Elorduy et al., 1981, 1982, 1984, 1997) and quality. Moreover, the protein included essential amino acids, such as lysine, methionine, and leucine, which are limited in protein sources of vegetal origin (Hall, 1992). Insect meal has protein levels and amino acid profiles that are better than soy meal, and it is even similar to fish meal in some species (Sánchez-Muros et al., 2014). Nevertheless, amino acid profiles vary among species (see Chapter 3). The comparison between the amino acid profile of fish meal and various insect species indicates that the amino acids are taxon-related. However, the amino acid profile of the flies (Order Diptera) is similar to that of fish meal (Barroso et al., 2014). The protein digestibility is another criterion to consider. Wang et al. (2007) studied the digestibility of amino acids in grasshopper meal and fish meal in broilers, and the results indicated higher values for grasshopper meal than fish meal, with the exception of serine, glutamic acid, and histidine. However, little information about the digestibility of insects is available. Fish studies indicate that the diet can include a percentage of insect meal without negative effects on digestibility, but this percentage depends on the insect species and the animal species that consumes it. For example, a 33% substitution with black soldier fly did not affect protein digestibility in turbot (Kroeckel et al., 2012), which is contrary to the results observed in Atlantic salmon fed a diet containing this insect (low protein digestibility was found) (Lock et al., 2014). On the other hand, the 75% substitution of fish meal with variegated grasshopper, migratory locust, superworm, or house fly in the diets of African sharptooth catfish and Nile tilapia did not affect digestibility (Ogunji et al., 2008c; Alegbeleye et al., 2012; Emehinaiye, 2012; Jabir et al., 2012b). Moreover, high digestibility *was* observed in diets containing silkworm for several fish species, including rohu (Begun et al., 1994), Mozambique tilapia (*Oreochromis mossambicus* Peters) (Hossain et al., 1992), Nile tilapia (Boscolo et al., 2001), black bullhead (Borthakur and Sarma, 1998b), snakeskin gourami (Jintasatapom et al., 2011), and walking catfish (with a 100% replacement of fish meal) (Habib et al., 1994). Nevertheless, the digestibility of silkworm varied based on the treatment of the meal, and the defatted meal exhibited better digestibility than the nondefatted meal (Hossain et al., 1997).

Furthermore, the nitrogen content of chitin molecules could provoke an overestimation of protein, however de cuticular chitin content is low, as Finke (2007) demonstrate the standard 6:25 conversion ratio between nitrogen and protein is adequate for insect CP.

The protein and amino acid availability especially for the amino acids from proteins that are either highly sclerotized or which may be bound to chitin (Finke, 2007). However, this nitrogen composes a low percentage of the total, so it does not affect the in vitro protein digestibility (Sánchez-Muros et al., 2015).

Source of Lipids and Fatty Acids

Another interesting aspect of insects as a food or feed ingredient is the level and quality of lipid content in some species, which can reach up to 77% of the body composition in some insects, such as *Phassus triangularis* Edwads larvae (the caterpillar of a moth species from Mexico) (Ramos-Elorduy et al., 1997). The lipid percentage in insects varies with the developmental phase, and, for holometabolous species which have larval and pupal stages, it is higher in larvae and pupae than in adults (Sánchez-Muros et al., 2014). Moreover, the lipid percentage in larvae and adults tends to be higher than fish meal (~8%) or soy meal (~ 3%). The high lipid content has some advantages, including as high-energy supply, and it is useful when high-energy diets are required (eg, broiler chickens). However, this elevated lipid content limits inclusion in livestock or fish diets, because the increased lipid percentage is above the required levels. Manzano-Agugliaro et al. (2012) proposed the use of insect fat in biodiesel production, and the resulting protein-rich paste could also be used in animal feeding (aquaculture or livestock).

Regarding fatty acid profiles, insect meal shows reduced levels of linoleic acid (18:2 n6) compared to soy meal. Furthermore, compared to fish meal, it also exhibits major levels of PUFAS n-6 (Omega-6 fatty acids) and low levels of HUFAS n-3 (Omega-3 fatty acids) (especially 20:5 n3 [EPA] and 22:6 n3 [DHA]). However, the levels of Omega-3 and 6 fatty acids are higher for many insects than for other animal livestock such as beef, dairy, pork, and chicken. The inclusion of HUFAS fatty acids in the diet is necessary because they affect important biological functions in vertebrates. Moreover, the Omega-3 fatty acids found in fish are considered a fatty acid source for humans. Terrestrial insects are clearly deficient in 20:5 n3 (EPA) and 22:6 n3 (DHA) compared with fish meal. However, 20:5 n3 is present in aquatic insects, and 22:6

n3 appears at a very low percentage in a few *Notonecta* species of order Ephemeroptera (the Mayflies) (Bell et al., 1994). The low Omega-3 fatty acid content imposes a limit on its inclusion in diet formulation, and this is particularly relevant to fish when fish meal is replaced by insect meal. In fact, the 25% replacement of fish meal with black soldier fly meal in trout diets affected the Omega-3 fatty acid levels in the fish (St-Hilaire et al., 2007b). Nevertheless, the fatty acid composition of insects varies with species, development stage, and feeding (Stanley-Samuelson et al., 1988; Ghioni et al., 1996; Bukkens, 2005; Raksakantong et al., 2010; Sánchez-Muros et al., 2014), which allows us to modify the insect fatty acid profile. For instance, St-Hilaire et al. (2007a) found increased Omega-3 fatty acids (EPA, DHA, and ALA) in black soldier fly prepupae when fish offal was included in the diet. These Omega-3 fatty-acid-enhanced prepupae may be a suitable fish meal and fish oil replacement for carnivorous fish and other animal diets. Black soldier fly meal obtained from flies fed fish offal allowed higher fish meal replacement percentages, and it also improved the Omega-3 and Omega-6 fatty acid content in fish muscles (Sealey et al. 2011). This ability to accumulate selected fatty acids from the diet allowed researchers to use the larvae as suitable vectors for the introduction of valuable Omega-6 fatty acids to animal muscle. de Haro et al. (2015) found an increase of arachidonic content in the muscle of gilt-head bream fed a diet containing common green bottle fly, which contains a high ARA percentage (10.6% total fatty acids when cultured with pig liver). The fish fed common green bottle fly meal enriched with ARA exhibited increased levels (80%) of this fatty acid in the muscle compared to fish fed the control diet (de Haro et al., 2015). Therefore, the use of this feed allowed fish to obtain a functional food that was rich in this fatty acid.

Chitin

In some studies, the presence of chitin might have affected the growth performance by influencing the feed intake, availability, and digestibility of the nutrients (Kroeckel et al., 2012). With a caloric content of 17.1 kJ g^{-1}, chitin could be a source of carbohydrates, and it could also constitute a substantial percentage of the total energy intake; nevertheless, its digestibility, which is discussed later, should also be considered. The hydrolysis of chitin requires the involvement of chitinase and chitobiase enzymes. High digestive chitinase levels were observed in cobia (*Rachycentron canadum* L.) (Fines and Holt, 2010) and in a broad range of marine teleost fish, and it was measured in the blood and lymphomyeloid tissues (in addition to digestive tissues) (Fange et al., 1976; Danulat and Kausch, 1984; Lindsay, 1986; Jeuniaux, 1993; Gutowska et al., 2004). Mammalian gut chitinases have been identified in humans, mice, cows, and chickens (Boot et al., 2001; Suzuki et al., 2001). However, despite high chitinase activity, low chitin digestibility was described in rainbow trout (Lindsay et al., 1984). On the other hand, chinolytic activity has also been described in gut bacteria, and it may play a role in the hydrolysis and apparent absorption of carbohydrates from chitin (Sugita et al., 1999).

However, chitin could affect the digestibility of other nutrients, including proteins (Longvah et al., 2011) or lipids (Kroeckel et al., 2012), leading to a reduction in growth. The results of these experiments that fed fish diets containing different chitin levels showed highly variable results, which could be dependent on the fish species or the chitin origin (crustacean or insect).

Moreover, chitin may have a positive effect on the function of the immune system. For instance, the use of insects to feed chickens may diminish the use of antibiotics in the poultry industry (van Huis et al., 2013), which is discussed in the section on antibiotic resistance.

Vitamins and Minerals

The vitamins and minerals needed for livestock varies based on species, age, physiological status, and the production quality and quantity. Rumpold and Schlüter (2013) published an exhaustive review on the mineral and vitamin contents found in different insect species. High variation was observed among species, but all analyzed insects were generally low in calcium, potassium, and sodium (with the exception of house fly larvae) (Hwangbo et al., 2009). Furthermore, most insects exhibited very high amounts of phosphorous. The magnesium content varied, and especially rich magnesium levels were found in the Order Hemiptera (“true bugs” such as stink bugs, etc.) and some species of the Order Orthoptera (eg, crickets, grasshoppers, locusts, and katydids). The micronutrient content (including copper, iron, magnesium, manganese, phosphorous, selenium, and zinc) in some species allowed the use of these species as sources of micronutrients for livestock (Rumpold and Schlüter, 2013, 2015)

Regarding vitamins, the content depends on the species, and some species are rich in some vitamins and deficient in others (see Chapter 3, and Rumpold and Schlüter, 2013). To a great extent, the insect vitamin profile also depends on the composition of the insect diet (Ramos-Elorduy et al., 2002).

In general, insects are rich in Vitamin B2 (0.11–8.9%), pantothenic acid, and biotin (FAO, 2004b; Bukkens, 2005). Some species showed high levels of Vitamin B12, (eg, yellow mealworms and house crickets) (Finke, 2002; Bukkens, 2005), folic acid (grasshoppers, crickets, locusts, and beetles) (FAO, 2004b), and Vitamin B1 (0.1– 4 mg of dry matter). On the other hand, insects are deficient in Vitamin A, Vitamin C, niacin, and Vitamin E (FAO, 2004b).

To include insects in animal feed, it is necessary to understand the contribution of minerals and vitamins to the diet, and it is important to specifically select the desired mineral and vitamin provisions. Moreover, the capacity to bioaccumulate minerals in insect exoskeletons, adipose cells, gonads, and digestive tracts must also be taken into account (van Huis et al., 2013). Therefore, the mineral content of the feed used to culture insects must be exhaustively controlled to avoid mineral toxicity or interaction between minerals. On the other hand, the capacity of insect of bioaccumulation of vitamins, mineral, and fatty acids could be used to engineer their nutrient content for feed.

See also Chapter 3 of this book for a more detailed discussion of insect nutrient content, particularly as it relates to human nutrition.

Feed Security and Safety

The feed used for livestock is required to meet standards of food safety, which includes the control of microorganisms (natural or contamination from handling), antinutritional factors, and toxic compounds from endogenous or exogenous origins. The food safety conditions of non-European insects has been studied (see Van der Spiegel et al., 2013), but much more work on this topic is needed. See Chapters 7 and 8 of this book for a detailed discussion on the food safety, regulatory, microbiological, and allergen issues related to insects as a human food ingredient.

Heavy Metals, Pesticides, and Contaminants

For insects and in general, there are several main subclasses of chemical contaminants which are monitored for animal feeds, human foods, and veterinary medicines. These include pesticides, heavy metals, dioxins and polychlorinated biphenyls, polyaromatic hydrocarbons, and mycotoxins of different species (Charlton et al., 2015). For instance, oriental leafworm moth larvae/caterpillars (*Spodoptera litura* Fab.) showed a higher capacity for the accumulation of cooper and zinc. However, chickens fed with insects containing high levels of these minerals exhibit lower levels of these minerals than the insect. This could be due to fecal excretion or low ingestion of insects (Zhuang et al., 2009). Further investigation of this field is required to avoid possible toxicity via insects, and this is needed even though toxicity is easy to prevent by rearing the insects in controlled conditions and feeding them safe feeds.

Pesticides are also bioaccumulated in some species of insects. For instance, high concentrations of organophosphorus pesticide residues were detected in locusts collected for food in Kuwait after the 1988/1989 outbreak (Saeed et al., 1993), the pesticides accumulated in the insects would be transferred to the food chain. Elevated glutathione S-transferase activity was observed when fish received higher dietary house fly larva meal concentrations, suggesting the presence of pesticides, drugs, or toxins in the hen waste used to feed the flies (Ogunji et al., 2007). Other repercussions of contaminated insect meal could also affect feed intake. For example, broiler chicks that were fed locusts that had been sprayed with an insecticide exhibited lower intake than those fed unsprayed locusts (Gibril, 1997). The capacity of insects to bioaccumulate drugs (eg, antibiotics) from the rearing substrate must also be considered. For instance, nicarbazin, which was used as an anticoccidial in poultry feed, was detected in house flies that were fed poultry manure (Charlton et al., 2015). Nonetheless, as most pesticides are designed to kill insects, insects are very sensitive to these compounds. Thus, it is unlikely that pesticides will be present or tolerated in farm-raised insects, as the pesticides woud likely limit productivity of the farm by killing the insects. Additionally, farm-raised insects and those mass produced indoors should be very easy to control in general, including eliminating their contamination by pesticides or any other chemicals or pathogens.

Microorganisms

Since insects are genetically very different than humans, vertebrates, and mammals, pathogens affecting insects are considered by many to be safe for humans (particularly viruses) (Banjo et al., 2006; Opara et al., 2012; van Huis et al., 2013) and probably for livestock. Nevertheless, insects could harbor some pathogens including microorganisms such as viruses, fungi, protozoa, or bacteria (Vega and Kaya, 2012), and in particular larvae could act as reservoirs of these pathogens (McAllister et al., 1994). Pathogens mainly associated with the cuticle (exterior of the insect) tend to be fungi (eg, *Aspergillus, Penicillium*, and *Fusarium*) (Mpuchane et al., 1996; van Huis et al., 2013), or bacteria (eg, *Staphylococcus aureus* Rosenbach, *Pseudomonas aeruginosa* Migula, and nonpathogenic *Bacillus* species) (Banjo et al., 2006; Opara et al., 2012), which produce toxins or cause the deterioration of the insect meal. For livestock, these pathogens hinder their conservation, and they are a risk to the health of the animal.

On the other hand, insects could be a transmission vector of some pathogens. For instance, house fly maggots were implicated in the transmission of *Escherichia coli* (Migula) from reservoir animals to other animals and humans (Moriya et al., 1999). *Cronobacter* spp., *Salmonella* spp., and *L. monocytogenes* (Murray) were also detected in house flies and blowflies that were collected from the dumpsters of urban restaurants (Pava-Ripoll et al., 2012). Despins et al. (1994) demonstrated the transmission of enteric viral pathogens to turkey poults that fed on infected lesser mealworm larvae. Another mode of contamination associated with insects is inadequate handling during insect meal manufacturing (van Huis et al., 2013). Regarding insects that were fed slaughterhouse waste, the possible transmission of prions has been discussed (Charlton et al., 2015). Therefore, this aspect must be carefully studied. Their presence may also be passed along to food products made from the animals fed with these insects, though many of these pathogens are common in such livestocks already fed on noninsect feeds. However, most of these pathogens, being associated with the exterior of the insects, likely come from their environment. Thus, a clean insect farm with good hygiene can likely mitigate or eliminate most if not many of these pathogens from the facility.

Insect Derived Toxins, Venoms, and Allergens

Toxic and venomous insects from the Orders Lepidoptera (butterflies and moths), Hemiptera (true bugs such as stink bugs), and Hymenoptera (ants, bees, wasps, and hornets) (Blum, 1981) are classified as neurotoxic, hemolytic, digestive, hemorrhagic, and allogeneic. The toxins chemically consist of alkaloids, terpenes, polysaccharides, biogenic amines (eg, histamine), organic acids (eg, formic acid), and amino acids, but the majority are peptides and proteins (Blum, 1981; Schmidt, 1986). Toxic/venomous insects typically use their chemical defense systemsto immobilize or kill prey and/or for defense against predator attacks.

Blum (1981) provided several examples of toxic species that should be avoided as human food, including cyanogenic species (eg, butterflies), vesicant species (eg, *Lonomia* moths), and those that produce steroids (eg, *Ilybius fenestratus* Fab.), corticosteroid hormones (eg, great diving beetle, *Dytiscus marginalis* L.), necrotoxic alkaloids (eg, fire ants, *Solenopsis* spp.), and toluene (eg, cerambicids). There are no studies on the toxins from these insects for livestock, but it is expected that toxins that affect humans also affect livestock. In chickens fed house flies, increased liver weight, which could indicate a toxic effect, was observed. In rats, the inclusion of 10% house fly meal resulted in histological changes in the liver and the kidneys (Bouafou et al., 2011a), which could indicated a certain level of toxicity.

The allergies provoked by insects have been mainly studied in humans (see Chapter 8 of this book for a detailed discussion on insect allergenicity in humans). However, it is also an important issue in animal feed, because the allergic response in farm animals could result in animal welfare issues, lower weight, and decreased meat performance (Charlton et al., 2015).

Digestive Enzyme Inhibitors and Antinutritional Compounds

Compared to other enzyme inhibitors, protease inhibitors have been studied the most, and they are widespread (Eguchi, 1993). In insects, protease inhibitors have a defensive function, but the effects of these when insects are included in animal diets have not been examined. Studies of protease genetic patterns in tse-tse fly (*Glossina morsitans* Westwood), common fruit fly, tobacco hornworm hawk moth (*Manduca sexta* L.), and silkworm indicated properties similar to those of serpins (Eguchi, 1993; Gubb et al., 2010).

Other antinutrients found in insect species, such as oxalate, phytate, tannin, and hydrocyanide, were detected, but the amounts were far below toxic levels (Omotoso, 2006; Ekop et al., 2010).

Preservation and Storage

The artificial breeding of insects may allow greater control over hygiene practices, and increased safety associated with edible-insect supplies might mitigate potential hazards. The greatest risk to humans and animals is the emergence of opportunistic disease-causing microbes in insect rearing systems, and hence insect diseases should also be avoided and controlled (Eilenberg et al., 2015).

Similar to other meat products, insects are rich in nutrients and moisture, and this provides a suitable environment for microbial growth and survival (Klunder et al., 2012). Studies indicated that the storage of dried housefly larvae with excessive moisture levels (23%) promoted the growth of bacteria and fungi, so processing to and storage at a maximum moisture level of 4–5% was recommended to minimize microbial activity (Makkar et al., 2014).

After washing, live insects are often transported in ice coolers shortly after collection. Furthermore, the preservation of meal of high-fat content insect species (especially those with high Omega-3 fatty-acid content) may require the addition of antioxidants and storage in dry areas, though more studies are needed to determine shelf-life of various insect-derived products overall.

Antibiotic Resistance

Antibiotics are poorly absorbed in the animal digestive tract, and they are released into the environment via animal feces (Binh et al., 2008; Looft et al., 2012; Zhu et al., 2013). Therefore, insects that are reared on manure for use as animal feed have a high likelihood of acquiring and carrying bacteria with antibiotic resistance. Furthermore, several studies demonstrated the proliferation of bacteria and the horizontal transfer of resistance genes via the insect digestive tract, and the transmission of resistant bacteria by insects to new substrates was also observed. Zurek and Ghosh (2014) proposed "that insect management should be an integral part of pre- and postharvest food safety strategies to minimize spread of zoonotic pathogens and antibiotic resistance traits from animal farms. Furthermore, the insect link between the agricultural and urban environment presents an additional argument for adopting prudent use of antibiotics in the food animal industry." On the other hand, adequate treatment methods, such as disinfection of insect meal, could help avoid the transmission of resistant bacteria from insects to livestock and good hygine at insect production facilities might help mitigate the need for antibiotic use.

Animal Welfare

The role of insects in animal welfare could be an additional benefit of insect use in animal culture in several ways. For example, it has been shown that chitin-increased activity in the innate immune system of sea bream has been described by different authors (Sakai et al., 1992; Esteban et al., 2000; Kawakami et al., 1998). However, most studies used non-insect chitin or chitin derivatives, and the administration of chitin was via injection. In rainbow trout, chitin administration stimulated macrophage activity (Sakai et al., 1992) and also stimulated respiratory burst, phagocytic activity, and cytotoxic activity in sea bream (Esteban et al., 2000). Furthermore, some evidence suggests that chitin confers protection against infections. For instance, rainbow trout and yellow tail individuals injected with chitin exhibited increased resistance to *Vibrio anguillarum* Bergeman (Sakai et al., 1992) and *Pasteurella piscicida* (Kawakami et al., 1998), respectively.

A few studies have added chitin to diets, and the results indicated an improvement of the *Epinephelus bruneus* Bloch immune response (Harikrishnan et al., 2012). In addition, the observed nonspecific modulation of hemolytic complement activity, leucocyte respiratory burst activity, and cytotoxicity indicated the enhancement of sea bream immune activity (Esteban et al., 2001). It is important to note that these studies added pure chitin to the diet. Nevertheless, the inclusion of insects supports the results obtained with pure chitin. For instance, Ming et al. (2013) found that a 2.5% supplementation with house fly meal increased the lysozyme, serum alkaline phosphatase, and glutathione peroxidase in serum. Moreover, superoxide dismutase and catalase activities in the liver increased, and it also reduced the malondialdehyde levels in the serum and liver. Furthermore, *Aeromonas hydrophila* (Chester) Stanier contamination resulted in lower mortality in fish that were fed house flies (Ming et al., 2013). This result indicated that chitin from insects played a role in the immune system, which was similar to the results observed when pure chitin was administered via injection.

The inclusion of chitin derivatives in the diet (eg, chitosan) was studied in different species. The results indicated that the particle size has different effects. For instance, particles measuring between 10^3–10^4 Da modulated the immune response and reduced the establishment of pathogens (Wang et al., 2003). However, if the molecular weight was below 10^3 Da, it stimulated the growth of *Bifidobacteria*, which has a number of health-promoting properties (Shigehiro et al., 1990; Zhou and Lin, 2000; Hou and Gao, 2001). The antibiotic/prebiotic activity was described for chitin in rats and chickens (Chen and Chen, 1999; Chen et al., 2002), and the hypolipidemic properties were described in broilers (Hirano et al., 1990; Hossain and Blair, 2007), hens, and rabbits (Hirano et al., 1990) that were fed chitosan instead of chitin (Hirano et al., 1990). However, there are few studies that have examined the effects of ingested insect chitin in livestock, and thus this is a field that requires further study.

Oxidative stress is considered a welfare indicator. The administration of insect meal that resulted in decreased oxidative stress was described (Manzano-Agugliaro et al., 2012), and the authors related these results to lower long chain HUFAS n-3 values and low peroxidation levels. The 71% supplementation of house fly meal in place of fish meal (compared to the control diet) resulted in an enhancement of the antioxidant capacity of Prussian carp (Dong et al., 2013). On the contrary, silkworm pupae meal substitutions above 50% in common carp caused oxidative stress, which significantly reduced fish growth, decreased superoxide dismutase and intestinal protease activities, and increased the amount of heat shock protein (Ji et al., 2013). These contradictory results could be due to the possible bioaccumulation of contaminants in insects, so the substrates used to rear insects must be free of contaminants.

PROMISING OPPORTUNITIES FOR RESEARCH AND TECHNOLOGICAL ADVANCEMENT

We would like to conclude by reflecting on some aspects that we consider important if insects are to be used as common animal feed ingredients in the near future. Although there are a large number of publications that address this issue, fundamental knowledge gaps regarding the potential use of insect-based animal feed remain. The insect world is huge and diverse, and that leaves much to be studied and discovered. Therefore, it will take many years to optimize the exploitation of insects as a feeding resource. Indeed, insects are already being utilized commercially as livestock feed by a rapidly growing number of companies around the world. Thus, in our opinion, some particular areas of research must be addressed.

Ecological Aspects and Sustainability

Environmental Benefits

As mentioned in other chapters of this book on use of insects as human food, compared to livestock, insect cultures are associated with low greenhouse gas emissions, low land-based activity, low ammonia emissions, and efficient conversion of feed into protein. Furthermore, insects can feed on organic by-products and other biomass that does not compete directly with the human food supply. From the point of view of animal feeding, insect use has additional benefits. For instance, decreased use of the main protein sources in animal feeding (fish meal and soy meal) would have significant environmental repercussions. Soy cultivation causes the deforestation of areas with high biological value (Carvalho, 1999; Osava, 1999), high water consumption (Steinfeld et al., 2006), pesticide and fertilizer utilization (Carvalho, 1999), and transgenic variety use (Garcia and Altieri, 2005), which cause significant environmental deterioration (Osava, 1999). On the other hand, fish meal is a resource that depends on the catch, and an exhaustive stripping of fisheries promotes the deterioration of the marine environment resulting in extinction of many marine species.

Utilization of the Native Insects by Local Farms

Taking advantage of natural resources without causing environmental deterioration is a great challenge. Currently, natural resources are overused owing to overcrowding, and are therefore ceasing to be renewable or sustainable. The traditional use of insects by local communities was not dangerous for the environment because it utilized small amounts of insects for either human or animal consumption. However, current interest in the use of insects as feed could increase the demand and the price, which could generate environmental problems such as extinction or entomofauna (insects) degradation. Therefore, the exploitation of wild entomofauna must be controlled with strict programs that sustain a healthy environment. Additionally, it would be beneficial in most cases to replace the use of wild collected insects with more efficiently captive farmed insects. In many cases, due to the high levels of biodiversity in Class Insecta, these could still be local native species, thus preventing the need to move nonnative and possibly invasive species from one area to another.

Expansion of the Number of Selected Species for Mass Rearing

In contrast with livestock culture in extensive or traditional systems, insects are part of the natural diet of animals, and small amounts of insects are consumed without harmful environmental effects. However, to supply the volume of insects needed for animal feeding, it is necessary to produce tons of insects; this could only be accomplished via mass-rearing systems.

The risks associated with insect cultivation stems from the rearing of foreign species. The FAO (2013) recommended the rearing of local species, particularly in tropical countries, because they pose virtually no risk to the environment, and there is no need for climate control. On the other hand, the methods associated with the use of insects to control plant pests are well developed, and there are established systems of control over cultured insect populations, which could be applied to the mass rearing of insects as animal feed.

Despite the development of insect culture systems, it is essential to continue research initiatives aimed at developing the “micro-livestock” of numerous major species, different taxa, and varied nutritional habits. Until now, mass rearing has focused on very few species. From an ecological point of view, it would be ideal to produce local species that are adapted to the environmental conditions and feed on local wastes and by-products, which would make production more efficient. Moreover, this would subsequently promote greater sustainability in integrated production systems, and it would result in lower production costs and the economic development of rural communities through small-scale and family-run farms and fish farms.

However, the ecological footprints of the insects or the water requirements for these intensive culture systems are not well established. Therefore, future studies that examine the development of mass insect cultures are needed to determine the real impact of mass-rearing insect production.

Environmental Enrichment for Livestock Animals

Insects could play an important role in environmental enrichment. Animals have feeding behaviors that include foraging. Neuringer (1969) demonstrated that when given a choice between "working" for food and having the food provided ad libitum, many animals chose to work for their food. Searching for food is a natural behavior that animals must express, and denying an animal appetitive opportunities might be a source of frustration or stress (Hughes and Duncan, 1998; Shepherdson et al., 1993; Shepherdson, 1998). In addition, tossing insects on the ground currently provides the opportunity and motivation for ground foraging and investigation behaviors (Mellen and MacPhee, 2001).

Therefore, future studies should focus on determining the effects of providing whole insects on the welfare of fish, chickens, and pigs. Artificial and intensive livestock production systems are increasingly being implemented. Moreover, the environment of the animals is very stressful, which induces annoyance and abnormal behavior, and these conditions can lead to serious health problems and decreased productivity.

Health problems associated with the legs and meat quality of broiler chickens reared in intensive systems are an example of this issue. Leg problems are one of the most common causes of culling, early mortality, and late mortality in broiler stocks, and they are considered one of the more serious welfare problems facing the broiler industry (SCAHAW, 2002). Walking ability in poultry is considered an important welfare parameter (Mench, 2004), but it is also critical for obtaining optimum flock performance, maintaining good energy efficiency and feed utilization, reducing bone disorders, improving bone strength, reducing skeletal fractures, improving food safety, and reducing processing plant condemnation issues (Oviedo-Rondón, 2007). One way to improve leg condition is to increase the locomotive activity of birds (Bizeray et al., 2002). However, the environment in the intensive systems provides minimal stimulation to the animals. One purpose of the enrichment is to provide the animals with objects, sounds, or odors that are not directly linked with the performance of some behavior, but instead provide the animals with a more stimulating environment (Newberry, 1995). In this context, we believe that insects could provide a fundamental enriching element. In nature, chickens (and other Galliformes) mainly eat insects during the first week of life to cover their high protein needs, and the percentage of insects in the diet decreases during the second and third weeks of life. Therefore, we believe that providing whole insects (live, if possible) in addition to their food supply, would favor the natural feeding and harvest behavior of the birds. Moreover, this higher level of physical activity would improve the muscular and skeletal systems of chickens, and it would also increase poultry productivity.

Chitin

Determining the digestibility of chitin and its effect on the digestibility of other nutrients for each livestock or aquaculture species is the first step. It is also necessary to obtain the adequate or acceptable levels of chitin in the diet.

On the other hand, the removal of chitin during meal manufacturing should also be investigated. The chitin could be removed from insect meal via alkaline extraction (DeFoliart et al., 1982; Belluco et al., 2013), but it can also be done using mechanical methods.

The addition of hydrolytic enzymes to diets is a global practice in animal feed production. The addition of chitinase and its effect on digestibility has not been studied, and it could be a solution to increase chitin digestibility. Alternatively, chitin could be degraded by chemicals or enzymatic methods before being added to diets as product of hydrolysis (eg, chito-oligosaccharides, acetylglucosamine, or chitosan) (Shiau and Yu, 1999; Se-Kwon and Niranjan, 2005; Lin et al., 2012a,b).

Chitin also being its own potentially high value by-product. Chitin and its derivates (chitosan) are used as antioxidant, anticancer, antiinflammatory, drug delivery, and plastics, Park and Kim (2010). If insect-based animal feeds take off and expand commercially, chitin as a by-product of animal feed production will be a much more sustainable and potentially larger scale source of chitin than current marine sources.

Insect Nutritive Value Improvement Using Different Rearing Systems

There are indications that food sources may affect the nutritional composition of insects. St-Hilaire et al. (2007b) observed that fatty acid composition in the black soldier fly could be manipulated by changing the substrate composition. On the other hand, the results of de Haro et al. (2015) indicated the accumulation capacity of essential fatty acids in common green bottle fly. However, several studies are needed to determine the bioaccumulation capacity of fatty acids or other compounds required for nutrient contribution or for the prevention of toxicity.

The capacity of insects to accumulate fatty acids, vitamins, minerals, and other nutrients is a very promising concept since the whole insects can be utilized to modulate/engineer the nutrient content of the resulting insect meal. Furthermore, knowledge of the effects of the substrate on lipid, protein, chitin, vitamins, or mineral levels should be improved.

Physical and/or Chemical Treatments of Insect Meals to Improve Their Assimilation

So far, few studies have examined the effects of different treatments to optimize the use of nutritious insect meals. Meal processing, including drying, hydrolyzing, ensiling, or defatting could improve the palatability, nutrient availability, digestibility, and composition of insect meals, which could make them more suitable for fish nutrition (Newton et al., 2005).

Drying

The drying of insect meal prevents the growth of bacteria and fungi. Regarding the house fly, a maximum 4–5% moisture content is recommended to minimize bacterial and fungal activity (Makkar et al., 2014). On the other hand, the drying method could modify the nutritive characteristics. For instance, Fasakin et al. (2003) found lower daily weight gain, protein efficiency ratios, and specific growth in fish fed a diet containing sun-dried MGM as compared to oven-dried meal. The sun-dried meal was richer in lipids and poorer in protein than the oven-dried meal (Aniebo and Owen, 2010), but oven drying increased the risk of lipid oxidation (Henry et al., 2015) and the loss of volatile fatty acids. Palatability was also affected by the drying method, and increased with oven and sun drying (Ng et al., 2001). Therefore, the recommended moisture percentage for the insect meal of each species, the drying methods, and the effects on nutritive and feeding parameters should be studied.

Silage

Ensiling is a method used to increase the shelf life of livestock feed. Few studies have examined the silage of insect feed, but promising results indicated the increased preservation of silkworm pupae meal and improved zootechnical indices. When fish meal was replaced with silkworm pupae or fermented silkworm pupae silage in a polyculture system for major Indian carp, mrigal carp, rohu, and silver carp, the fermented silkworm pupae silage resulted in better survival rates, FCRs, and specific growth rates compared to feeding with the untreated fresh silkworm pupae or fish meal, which had little influence on the body proximate composition (Rangacharyulu et al., 2003).

The addition of organic acids, enzymes, and the like increased the nutritive value of the feed. The inclusion of additives in insect ensiling is an area that should be investigated to optimize the use of insects in animal feed. Yashoda et al. (2008) obtained good-quality silage by ensiling with molasses or curd as a lactic acid culture. Therefore, ensiling with additives, such as chitinases, to promote the degradation of chitin, should be further studied.

Defatting

The quality and quantity of insect lipids limits the inclusion of insects in livestock diets, but the defatting of insects is one solution. The extracted lipids could be used as biofuel, and the resulting protein could also be used as a protein source in animal feed (Manzano-Agugliaro et al., 2012). The defatting of insect meal enabled the increased dietary inclusion of insects without affecting the growth of African catfish (Fasakin et al., 2003). However, defatting methods must be further studied. In Atlantic salmon, better results were obtained with meal that was lightly defatted and dried at a low temperature compared to meal that was highly defatted and dried at a conventional temperature (Henry et al., 2015). However, the insect lipid levels and the possible oxidation of lipids (Aniebo and Owen, 2010) could have influenced these results. Henry et al. (2015) proposed the addition of antioxidants to insect meal to reduce the negative effects of drying processess on lipids.

Disinfection

The microbiology of insects is significantly different from that of conventional food animals, and it deserves further study (Belluco et al., 2013). Moreover, other insect species should also be investigated as potential pathogen hosts to minimize disease transmission via the food chain (Khusro et al., 2012). In addition, the disinfection of insect meal should be considered, and the establishment of hygienic rules for insect processing is necessary.

CONCLUSIONS

There is currently a growing interest in insects as agricultural products, and the number of studies that consider the use of insects in animal feeding is also increasing. The studies reviewed in this chapter show the great potential that insects have as animal feed. Although they will not be able to match the nutritional characteristics of fish meal, insects could become a major animal feed source. In many cases, insect meals could partially replace fish meal, but they could completely replace some vegetable or soy meals found in many livestock and aquaculture feeds.

So far, the insect species tested in animal feeds are limited, so the number of evaluated and mass-reared insect species should be expanded. Moreover, it seems clear that more feeding trials in different species are needed to determine their future roles as protein components in animal feed.

Several lines of research show great promise in the future use of insects in animal feeding. The role of insect-based feeds in animal welfare, nutritional value improvement via physical means or breeding systems, feed security and safety, increased assimilation of insect meal via physical or chemical treatments, chitin modification, and so forth are all issues that should be addressed in future studies. Another challenge that must be met is the standardization of the nutritive composition of insect species with feeding interest in animals. This will allow us to optimize insects as renewable livestock feed resources.

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