Agronomy Research **18**(X), xxx–ccc, 2020
https://doi.org/10.15159/AR.20.003

Insects in chicken nutrition. A review

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Abstract. Increasing chicken meat production needs an alternative and easily available protein source as a potentional substitute for soybean meal or fishmeal. The insect meals seem to be the most appropriate alternative. Of all insect species, *Tenebrio molitor, Hermetia illucens* and *Musca domestica* are the most suitable species for commercial exploitation in poultry feed. On the basis of numerous studies, insect meals contain sufficient nutrients (high quality protein and fat) for broiler production. Potential of insect meals used for feed of chickens is discussed based on published data. Many reviews summarizing the latest insights about the insect meals as an alternative protein source in poultry have been written. However, the present work describes not only the insect production, nutritional value and digestibility of the insect meals, but mainly the effect on performance, carcass characteristics and meat quality of chickens fed insect meals, which has not been in any review summarized yet. The study describes also the risks and safety of the insect meals. Based on numerous studies, insect meals can have a positive influence on growth without negative impact on carcass and meat quality characteristics.

Key words: chicken, insect meals, meat quality, protein source.

INTRODUCTION

Protein is the major nutrient required for optimal broiler production and an increasing poultry production call for growing amount of protein to cover requirement of amino acids. One of the main sources of protein and fat in the feeding of poultry is soybean (Woods et al., 2019). Livestock production in the western hemisphere is consuming 85% of global soya production (Stamer, 2015). However, due to high cost of soybean and the competition between livestock and humans for consumption of arable crops, there is an increased request for the alternative and easily available protein sources (Khan et al., 2016, 2018; Woods et al., 2019). Currently, there is an increasing interest in the use of the insects as an alternative protein source either for total or partial replacements of commonly used protein sources as for example soybean or fishmeal in poultry diet, due to a high nutritive value. Insect meals are safe and do not have negative effect on the environment contrary to soybean (global warming, biodiversity loss, deforestation and destruction of ecosystems, increasing greenhouse gas emissions, large carbon footprint, FEFAC, 2012) or fishmeal (decline in native fish stock, biodiversity loss, high disease rate and coastal habitat impairment, Henry et al., 2015) production.

However, in the European Union, the insect meals utilization in livestock nutrition is banned (Regulation (EC) No. 1069/2009) because these compounds are considered to be processed animal protein (PAP, Regulation (EC) No. 999/2001) prohibited in feeding of farmed animals (Kierończyk et al., 2018). Nevertheless, insect feed is currently allowed in pet food and in fish feed. Only a few insect species are allowed in the European Union for aquatic animals' nutrition.Due to the potential ecological advantages and good acceptance among farmers and consumers (Verbeke, 2015), it is probable that the political framework may change in the future and make use of the insect protein possible also in poultry diets (Leiber et al., 2017). One of the reasons for a likely permit is that poultry consume insects as part of their natural diet.

Many reviews reported the information about the insect meals as an alternative protein source in poultry nutrition. However, there is a lack studies summarizing the results on slaughter parameters and meat quality of chickens. Therefore, the aim of this work was to update, present and discuss the previous studies regarding the insect as a potential alternative protein source and describe its effect on poultry performance, carcass traits and meat quality.

INSECTS PRODUCTION

Approximately 2,000 species of insects are known to be a highly digestible and edible protein source for humans or animals (Ramos-Elorduy, 2005). Insects have several useful physiological characteristics such as high reproductive ability, high feed conversion rate and easy rearing with low feed cost (Liu et al., 2011). Insect species are efficient feed converters because they are cold-blooded (Cullere et al., 2016) and do not use energy to maintain body temperature (Biasato et al., 2018a). Insects effectively utilize water and, in most cases, the feed is the main source of water (Józefiak & Engberg, 2015). Generally, the breeding of insects does not require a complex infrastructure and their care is simple (Khusro et al., 2012). Insects can grow on various substrates as for example cereals, decomposing organic materials, fruit or vegetables, poultry, pigs and cattle manure, industry by-products or waste products, which would be environmental problems (Sánchez-Muros et al., 2014; Cullere et al., 2016). However, in European Union is forbidden to use manure and other animal by-products in insects nutrition which are produced as a feed for livestock (Article 7 and Annex IV to Regulation (EC) No 999/2001; Regulation (EC) No 1069/2009). Khan et al. (2016) reported that use of insect meals or larvae meals (Kareem et al., 2018) can decrease the cost of poultry feed especially if it is reared on bio-waste. Insects can transform waste into valuable biomass (Nguyen et al., 2015) and convert low-quality plant waste into high-quality crude protein, fat and energy in short time (Makkar et al., 2014). The amount of manure is reduced by at least 50% and the resulting product contains nutrients such as phosphorus (60% to 70%) and nitrogen (30% to 50%; van Huis et al., 2013). The other advantage is the ability of larvae to decrease bacterial growth in the manure and thus reduce odour (Józefiak & Engberg, 2015).

The growth rate of insects depends on microclimate. The optimal temperature for most insect species rearing is 27–30 °C (Józefiak et al., 2016). The larvae of insects are the most effective for production and it is possible to produce more than 180 kg of live weight of *Hermetia illucens* larvae in 42 days from 1 m^2 (Józefiak et al., 2016).

The insect market for animal feed is continually increasing in the world, especially focused on *Tenebrio molitor* larvae (mealworm). *T. molitor* and *H. illucens* (black soldier fly) are two of the most promising insect species for commercial exploitation and for use in poultry feeds (Józefiak et al., 2016), their production is seamless and well understood (Kierończyk et al., 2018).

INSECT NUTRITIVE VALUE

Insects have high nutritive value, not only in crude protein but, also for fats, minerals, and vitamins (Khusro et al., 2012). Nevertheless, the nutrient concentration of insects depends on the production technology and feed composition for insect production and on the life stage of insects (Józefiak & Engberg, 2015). Insects are a potential protein source in fish, pigs and poultry (Bovera et al., 2016; Józefiak et al., 2016). Larval and pupal stages of *Musca domestica* (maggot meal), *T. molitor* or *H. illucens* (Kareem et al., 2018) are rich sources of crude protein (40–60%) which is similar to soybean meal (Ramos-Elorduy et al., 2002; Ghaly & Alkoaik, 2009; Tran et al., 2015). All species of insects are rich in essential amino acids (Al-Qazzaz et al., 2016) and according to Rumpold & Schluter (2013) have a better balance of essential amino acids (methionine and lysine) than most grains. However, Bovera et al. (2016) reported that the insect meals protein had a low content of essential amino acids of methionine, cysteine, lysine, and tryptophan. On the other hand, Tschirner & Simon (2015) showed that *H. illucens* larvae have a particularly advantageous amino acid profile with high proportions of lysine and methionine. Moreover, Woods et al. (2019) stated that the addition of fish guts to the substrate improved the amino acid content, mainly essential amino acid, in the larvae of *H. illucens*; however, the usage of animal by-products to feeding insects is not allowed in European Union. According to Makkar et al. (2014) and Khan et al. (2018) the *T. molitor* had a better nutritive profile than silkworm, *M. domestica* and soybean meal because contains a higher amount of crude protein, fats, amino acid, and mineral content.

Meal from larvae of *H. illucens* is according to Schiavone et al. (2017) excellent source of apparent metabolizable energy for broiler chickens. The fat content in the selected insect species was determined on the level of 30.8% and 33.6% for *T. molitor* and *Zophobas morio*, respectively (Kierończyk et al., 2018). Likewise, Ramos-Elorduy et al. (2002) and Ghaly & Alkoaik (2009) reported that larval and pupal stages of *T. molitor* and other insects are rich in fat (35% in dry matter). The lipid content of insects depends on many factors, such as the diet or the life stages of insects. Therefore, the chemical composition of the insects could affect the growth substrate and the time of harvest (Spranghers et al., 2017). Woods et al. (2019) found that the fat content of larvae *H. illucens* was modified by the growing substrate, while the crude protein content was constant. Kierończyk et al. (2020) have shown that crude protein, and other nutrients in *H. illucens* larvae can be modified by the organic waste used as a substrate.

The final composition of animal fat reflects the fatty acid composition of the diet. The fatty acid profiles of insect oils showed higher saturated fatty acids contents (SFA; mainly palmitic acid C16:0 and stearic acid C18:0), and higher concentrations of monounsaturated fatty acids (MUFA; mainly oleic acid C 18:1, n-9; Al-Qazzaz et al., 2016). The degree of unsaturated insect fatty acids is similar to fish oil, but insect fatty acids are richer in polyunsaturated fatty acids (PUFA; De Foliart, 1991; Kierończyk et al., 2018). For example, *T. molitor* larvae contained high levels of unsaturated fatty acid and had suitable unsaturated fatty acid to saturated fatty acid ratio which may have resulted in the maintenance of fat digestibility (Finke, 2002). The fat content of *H. illucens* prepupae was around 32%, where the main fatty acid group was saturated fatty acids (SFA) in which lauric acid (C12:0) was the predominant one (67% of total SFA; Surendra et al., 2016). The larvae of *H. illucens* have the disadvantageous n-6/n-3 ratio (Woods et al., 2019). Nevertheless, the fatty acid profile of insects depends on the growth substrate. Kierończyk et al. (2020) reported that the organic wastes can modify fatty acid profile and wheat bran compared to cabbage or carrots used as a substrate for *H. illucens* production reduce the lauric acid (C12:0).

The insects also have sufficient content of copper, iron, magnesium, phosphorus, and zinc for requirements of domestic birds (Barker et al., 1998). However, the majority of insects had low concentrations of calcium to meet chicken dietary needs, but this is important especially for laying hens, not for broiler chickens (Khusro et al., 2012). Moreover, calcium to phosphorus ratio is mainly detrimental in insect meals is mainly detrimental from nutritional issues, and due to this fact, it should be taken into consideration during calculations of poultry diets.

Chitin

The chitin content can affect the digestibility and nutritional properties of insects. Chitin is the most common form of fiber in insects (Al-Qazzaz et al., 2016); however, due to the nitrogen absence is also analysed by Kjeldahl method as a crude protein and is included to the nitrogen-to-protein conversion factor of 6.25, which overestimated the protein content. Because of this reason, Janssen et al. (2017) suggested conversion factor of 5.60 ± 0.39. Chitin is a polysaccharide (linear polymer of β-(1-4) *N*-acetyl-d-glucosamine units) of the exoskeleton of anthropods (Sánchez-Muros et al., 2014). Chitin has been considered as indigestible fibre for a long time. However, in some mammals and birds like chickens the gastrointestinal tract (GIT) produces enzyme chitinase (in chickens in the proventriculus and hepatocytes, Suzuki et al., 2002), which degrades chitin into its derivatives chitosan, chitooligosaccharides, and chitooligomers that are easily absorbed into blood circulation (Borrelli et al., 2017; Tabata et al., 2017). Kramer et al. (1995) showed that the chitin content creates up to 40% of the exuvial dry mass depending on the insect species and its stages and differs with the cuticle types. Average chitin yields were 18.01% and 4.92% of dry weight from the exuvium and whole body of the *T. molitor* larvae (Song et al., 2018). The chitin composition depends on species and development stadium of insect (Al-Qazzaz et al., 2016).

On the other hand, chitin have a positive effect on the functioning of the immune system and thus on the health in poultry. Prebiotic effect of chitin was observed by increasing caecal production of butyric acid (Bovera et al., 2010; Khempaka et al., 2011), by improving the immune response of birds (Bovera et al., 2015) or due to lowering the albumin to globulin ratio (Loponte et al., 2017). Chitin and its derivatives can help to maintain a balanced and the healthy GIT microbiota that keeps the amounts of potentially pathogenic bacteria (for example *Escherichia coli, Salmonella typhimurium*) low (Benhabiles et al., 2012) and decreases the risk of intestinal diseases. By reducing the number of pathogenic microbiota, chitin encourages the proliferation of commensal bacteria. A positive effect of chitin on increasing population of Bifidobacteria and *Lactobacillus* spp. showed Lee et al. (2002) and van Huis et al. (2013), who also stated that diet containing 3% of chitin decreased *Escherichia coli* and *Salmonella* spp. in the intestine. Chitin also has antifungal and antimicrobial properties (Khoushab & Yamabhai, 2010).

INSECT MEALS ANTIMICROBIAL PROPERTIES

Various populations of microbiota colonize all segments of the GIT in poultry (Józefiak & Engberg, 2017). The main taxa of the broiler chickens GIT are cellulolytic and amylolytic *Clostridia*, *Bacillus* spp., *Lactobacillus* spp., and *Enterococcus* spp. GIT microbiota seems to be crucial for GIT health determination, can affect intestinal morphology through modifications of villus height and crypt depth, and may modulate synthesis and composition of mucins (Forder et al., 2007). Mucins constitute a digestion- and absorption-assisting medium and represent the first line of protection against bacteria and other pathogens (Forstner & Forstner, 1994). The GIT microbiota is mainly influenced by the nutrition. Insects have high medium chain fatty acids (MCFAs) and lauric acid (C12:0) contents (Spranghers et al., 2017). MCFAs have been shown to improve the intestinal morphology and function, through their beneficial effects on crypt cell renewal (Jenkins &Thompson, 1993). On the other hand, Spranghers et al. (2018) in their study did not detect the differences in small intestine morphology between piglets under various diets. MCFAs have also antimicrobial effect on GIT microbiota, while lauric acid (C12:0) is particularly active against Gram-positive bacteria. The antimicrobial activity of MCFAs and lauric acid is related to the reduction of pH. In the proximal small intestine with pH from 4.0 to 6.0, most of the lauric acid will be undissociated, and can freely penetrate though the peptidoglycan membrane of the Gram-positive bacteria into the cytoplasm (Spranghers et al., 2018). In the *in vitro* experiment, Spranghers et al. (2018) exhibited that the high amount of lauric acid in the *H. illucens* fat extracts had antimicrobial effect against D-streptococci, but no effect on coliforms.

In addition to the above-mentioned positive effect of chitin, MCFAs, and lauric acid on the immune system, insects are also able to synthesize antimicrobial peptides (AMPs) which have revealed a broad spectrum of activity against both Gram-positive and Gram-negative bacteria, fungi, and viruses. Moreover, this activity does not lead to the development of natural bacterial resistance (Józefiak & Engberg, 2017). Benzertiha et al. (2019b) showed that AMPs are probably responsible for decrease of bursa of Fabricius size playing an important role in the differentiation of B-lymphocytes. Józefiak et al. (2018) found that inclusion of small amounts (0.05 to 0.2%) of insect full-fat meals can modulate the microbiota composition of the GIT in the broiler chickens and do not result in the development of natural bacterial resistance. Biasato et al. (2018b) showed in the caeca of free-range chickens fed with *T. molitor* the most predominant genera *Bacteroides*, unclassified members of *Bacteroidales* order, *Clostridium* and *Ruminococcus*. The genera *Clostridium* and *Ruminococcus* produce organic acids, including butyrate, acetate, lactate or formate (Józefiak et al., 2018). Furthermore, *Ruminococcus* genus can produce other short chain fatty acids, which are an important source of energy for enterocytes and are vital for intestinal health (Biasato et al., 2018b). In chickens fed with *T. molitor* meal increased the number of *Clostridium*, *Oscillospira*, *Ruminococcus*, *Coprococcus* and *Sutterella* genera in their caecal community (Biasato et al., 2018b). *Clostridium* genus, *Oscillospira* and *Coprococcus* include bacteria capable of producing butyrate that have a positive role on intestinal villus structure and pathogen control as mentioned above. Józefiak et al. (2018) reported that greater quantity of *Clostridium leptum* and *Eubacterium rectale* in chickens fed with insect meals can be a good indicator of the butyrate-producing microbiota, which indirectly affect epithelial cell structure and function, particularly in the lower regions of the GIT (Józefiak et al., 2018). The illeal digesta of the broiler chickens from treatment supplemented with insect meals had the highest counts of *Clostridium coccoides-Eubacterium rectale* cluster and *Lactobacillus* spp./*Enterococcus* spp. Counts increased with the addition of *T. molitor* meal. *H. illucens* supplementation increase *Bacteroides-Prevotella, Clostridium coccoides–Eubacterium rectale* cluster and *Streptococcus* spp./*Lactococcus* spp. in the caeca (Józefiak et al., 2018). *C. coccoides* are commensal GIT microbiota and are considered a group of bacteria playing important role in immunology, nutrition, and pathological processes (Józefiak et al., 2019). Free-range chickens fed with *T. molitor* meal showed increased abundances of *Firmicutes* and decreased abundances of *Bacteroidetes* phyla, and higher *Firmicutes:Bacteroidetes* ratios. *Firmicutes* phylum have an important role in the digestion of feed and the host health, while greater *Firmicutes:Bacteroidetes* ratios have been related to bacterial profile with higher capacity of energy harvesting (Biasato et al., 2018b).

The increased levels of commensal bacteria can have beneficial effect on health due to immune system stimulation. The results of Józefiak et al. (2018) showed that the low inclusion of the insect full-fat meals affected GIT microbiome and decreased the pH value in the crop and in caeca. This acidification can reveal the potential bacteriostatic role of insect meals in the GIT of poultry.

NUTRIENT DIGESTIBILITY

The nutrient concentration of insects depends on their life stage, rearing conditions and the substrate used for insect production (Makkar et al., 2014). Measuring digestibility is a way how to estimate the availability of nutrients.

Results of the digestibility trial of Woods et al. (2019) showed a higher apparent digestibility for dry matter and organic matter for *H. illucens* larvae fed quail compare to the control fed group. Contrary, Bovera et al. (2016) found 2% lower ileal digestibility coefficients of dry matter and organic matter in broilers fed the *T. molitor* diet than those fed the soybean diet. In laying hens, Cutrignelli et al. (2018) detected the reduced coefficients of the apparent ileal digestibility (AID) of dry and organic matter when fed the *H. illucens* meal diet. This decreasing were according to these authors mainly due to the strong reduction of the crude protein digestibility that was related to the presence of the chitin in the insect meals, which negatively influences the crude protein digestibility. If we compare digestibility coefficients of the dry matter between *T. molitor* meal and *H. illucens* meal, no differences were found (De Marco et al., 2015).

Woods et al. (2019) observed a higher apparent metabolizable energy for *H. illucens* larvae fed quail compare to the control fed group. Nevertheless, in this study, *H. illucens* meal has resulted more digestible than the *T. molitor* meal in case of fat. Similar results showed Benzertiha et al. (2019a) who did not find the differences among *T. molitor* oil and palm oil on AID of crude fat, and metabolizable energy. The apparent metabolizable energy of the *T. molitor* meal and *H. illucens* meal (De Marco et al., 2015) was higher than all the ingredients normally used in poultry feeds.

Hwangbo et al. (2009) in their experiment fed 4-week old chickens with a diet substituting 300 g kg^{-1} dried *M. domestica* and found very high apparent digestibility coefficient of crude protein for *M. domestica* larvae (0.98) compared to soybean. Pretorius (2011) substituted 500 g kg^{-1} of a maize meal-based diet with *M. domestica* larvae meal for 3-week old broiler chickens and detected a crude protein digestibility of 0.69. De Marco et al. (2015) found no difference between *T. molitor* meal and *H. illucens* meal in digestibility coefficient of the crude protein. Benzertiha et al. (2019a) studied the *T. molitor* oil as total replacement for palm oil in chicken diet. They observed no effect on apparent crude protein digestibility in chickens. On the other hand, Schiavone et al. (2014) observed lower crude protein digestibility when chickens were fed *T. molitor* larvae as well as Bovera et al. (2016) who found 8.2% lower crude protein digestibility in chickens fed *T. molitor* compared to soybean diet.

De Marco et al. (2015) found that the AID of amino acids in the *T. molitor* meal was higher and showed less variation than in the *H. illucens* meal. In this study, threonine (0.80) and methionine (0.80) for *T. molitor*, and methionine (0.42) and isoleucine (0.45) for *H. illucens* were the least digested indispensable amino acids. The AID coefficients of the indispensable amino acids (phenylalanine and arginine in the *T. molitor* meal, and arginine and histidine in the *H. illucens* meal) was greater than 0.80.

According to above-mentioned results, insect meals can be alternative crude protein source for soybean meal or fishmeal.

INSECTS IN POULTRY NUTRITION

Insects in various stages (adult, larval and pupal forms) are naturally consumed by wild bird and free-range poultry (Biasato et al., 2018a).

Birds including chickens have a low taste bud number and thus low taste acuity compared to mammals (Liu et al., 2011). Chickens have different sensitivities to the bitter taste (Woods et al., 2019). Cullere et al. (2016) made a feed-choice test in quails and observed that the birds preferred the diet including *H. illucens* meal compared to soybean meal. In particular studies, insects are fed to poultry in the form of meal or oil, but according to Moula et al. (2017), feeding life insects may be more adequate than after processing. On the other hand, some insects cannot be used directly because they secrete toxins or harmful minerals (Vijver et al., 2003). Therefore, they should be processed to make them safe for use in poultry diets. Live insects can also be difficult for handling and incompatible with automated feeding systems and can act as vectors in the transmission of infectious and viral diseases (Khusro et al., 2012). Live insects also may be difficult to mix them with ingredients in the diet, so processed insects can be easier to handle (Al-Qazzaz et al., 2016).

Pretorius (2011) showed that the housefly larvae can be added at the level of 25% of diet without negative effect on growth and feed efficiency which means that insect meals can replace other crude protein sources such as soybean meal or fishmeal. Johnson & Boyce (1990) revealed that increasing amount of insect meal added in the diet improved survival and growth rate of chickens. Mortality of quails was not affected by the inclusion of 10% dried *H. illucens* larvae (Woods et al., 2019). Correspondingly, the results obtained by Kareem et al. (2018) showed that excreta Enterobacteriaceae count was lower in birds fed with larvae meal supplemented diets than the control.

THE GROWTH PERFORMANCE

Insect meals can affect the growth performance, and the level of influence depends on the added insect meals amount and its quality.

The effect of insect meals in the diet on body growth can be due to the different impact on the digestive system and the GIT microbiota modulation. Ballitoc & Sun (2013) found that the small intestine weight increased at up to 10% when the broilers fed *T. molitor* compared to control. The results of Bovera et al. (2016) showed that the length and weight of ileum and caeca increased when chickens were fed with *T. molitor* larvae meal supplementation.

In the final phase of nutrient digestion, morphology of intestine plays the main role. Villus height and crypt depth are microscopic structure parameters that are good indicators of intestinal development, health and functionality, and influencing nutrient digestion and absorption (Schiavone et al., 2018). If the digestibility of nutrients is limited, it resulted in the increasing villi length and the villi to crypt ratio in the duodenum and jejunum and thereby increasing area for nutrient absorption (Laudadio et al., 2012; Zeitz et al., 2015). However, the changes in morphology, length and weight of intestine depends on the protein source-level substitution with insect meals and on the insect species. Biasato et al. (2018a) observed in the birds fed with 15% level of *T. molitor* inclusion shorter villi, deeper crypts compared to 5% level of *T. molitor* inclusion or control. According to Bovera et al. (2010), chitin contained in insect meals in a broiler diet increased in caeca the production of butyric volatile fatty acid which is considered the prime enterocyte energy source and can stimulate the growth of ileal mucosal cells and thus to have an impact on the body growth.

Despite the effect of feeding the insect meals on the structure and length of the intestines, the effect on growth itself is not clear. Some authors did not find the influence of insect meals on growth. No effect of *T. molitor* inclusion level from 5 to 10% in partial substitution of soybean meal on growth performance was detected by Ramos-Elorduy et al. (2002) in fast-growing chickens as well as Biasato et al. (2016) in medium-growing chickens, who substituted 7.5% of corn gluten meal with *T. molitor* meal. Likewise, Kierończyk et al. (2018) replaced soybean oil by *T. molitor* oil or *Z. morio* oil and they did not detect effect on growth, as well as Schiavone et al. (2017; 2018) in case of *H. illucens* oil supplementation. Similar results observed also Benzertiha et al. (2019a) who used *T. molitor* oil to replace palm oil in the diet of chickens. Cullere et al. (2016) reported no difference in daily weight gain in quails fed deffated *H. illucens* meal and control group. On the other hand, Bovera et al. (2015, 2016) showed improved growth performance when 29.6% of soybean meal was replaced by *T. molitor* meal, and also Khan et al. (2018) reported significantly higher weight gain in birds by substituting insect meals. Moreover, Biasato et al. (2018a) detected that the live weight of the birds improved with increasing level of *T. molitor* meal in feed. Similarly, higher live weight of chickens fed with mealworm showed Khan et al. (2018) or Altmann et al. (2018) for chickens fed with the diet containing *H. illucens* larvae meal. On the other hand, Bovera et al. (2015) examined a 30% *T. molitor* meal inclusion (equal to a 100% soybean meal replacement) in broiler diets, and they did not detect any differences in live weight after a 64-day feeding trial. Correspondingly, Awoniyi et al. (2003) showed that the replacement of fishmeal with larvae meal in broiler diets did not influence live weight. It seems that the influence of growth and thus live weight depends on the insect species and on the protein source-level substitution with insect meals.

Cullere et al. (2016) reported no difference in average daily feed intake (FI) from the conventional feed when intensively reared growing quails were fed on defatted *H. illucens* meal. Similarly, daily FI was not influenced by the partial or total replacement of soybean oil by *H. illucens* larvae fat (Schiavone et al., 2018). Broiler chickens fed with mealworm exhibited lower FI compared to those fed with soybean (Khan et al., 2016, 2018). The lower FI in chicken can be attributed to the high lipid content (Poorghasemi et al., 2013) or higher crude protein percentage of insect meals (Makkar et al., 2014). On the other, Kierończyk et al. (2018) have stated that the energetic value of *T. molitor* oil is similar to soybean oil. Chickens fed the diet with *T. molitor* meal had better feed conversion ratio (FCR) compared to the control group (Bovera et al., 2016). Moreover, Khan et al. (2018) evaluated different insects and found that FCR improved in *T. molitor*-substituted group followed by silkworm, *M. domestica* meal and soybean meal. Better FCR can be due to efficient utilization of crude protein and quality of amino acids.

CARCASS TRAITS

Most of the studies did not find significant differences in carcass traits of young chickens when fly larvae or pupae replaced soybean meal. No effect on carcass traits was observed after house *M. domestica* meal was added to the diet of broiler chickens (Hwangbo et al., 2009). Similarly, *T. molitor* meal inclusion did not affect the carcass traits of experimental groups in the trial of Bovera et al. (2016) or Biasato et al. (2016, 2018a). Contrary, in the study of Pieterse et al. (2014) animal protein-based diets (i.e. fishmeal and larvae meal) resulted in heavier carcasses compared to soy-based diet. Likewise, Altmann et al. (2018) detected heavier carcass in chickens fed with diet where 50% of the soy-based protein was substituted by *H. illucens* larval meal than in control group, probably because of *H. illucens* meal diet was substantially higher in crude protein and ether extract and chickens fed with this diet had higher final live weight.

When fishmeal was replaced by larvae meal in broiler diets, the dressing out percentage was not affected (Awoniyi et al., 2003). In agreement, Cullere et al. (2016) fed broiler quails on 0, 10, and 15% inclusion levels of *H. illucens* meal and did not find a difference between the conventional and insect-based diet on dressing out percentage. On the other hand, Hwangbo et al. (2009) observed higher dressing percentages for broilers fed house fly meal included at levels from 5% to 20%.

The results of the percentage of the main valuable parts in poultry fed insect meals are ambiguous. Awonyi et al. (2011) showed no effect of replacement fishmeal by larvae meal on muscle yield. Cullere et al. (2016), Onsongo et al. (2018) and Kareem et al. (2018) did not observe the effect of *H. illucens* meal inclusion on breast meat percentage in quails or chickens, respectively. However, when soy-based diet was partially replaced with insect meals, it resulted in higher breast and thigh muscle weights (Hwangbo et al., 2009) or higher breast meat percentage (Pieterse et al., 2014).

MEAT QUALITY

Meat quality can be described by chemical composition, physical meat characteristics (pH value, colour, tenderness) or sensory value. The chemical composition of meat can be influenced by the crude protein and energetic concentrations in the diet, whereas the impact of the crude protein source is still unclear (Özek et al., 2003). Regarding the change of protein in the diet, Pieterse et al. (2014) and Bovera et al. (2016) found that when the soybean meal was completely replaced by *T. molitor* meal as a crude protein source, it did not affect the proximate composition of meat. Pieterse et al. (2019) showed that the inclusion of *H. illucens* meal in the broiler chicken diet did not influence moisture, crude protein, fat and ash content of cooked meat. The assimilation of dietary fats by chickens is higher for unsaturated than for saturated fatty acids (SFA). Unsaturated fatty acids spontaneously formed mixed micelles with monoglycerides and conjugated bile salts and then are transported to the mucosal surface where they are absorbed by the small intestine (Tancharoenrat et al., 2014). With increasing *H. illucens* larvae inclusion rate, the proportion of SFA in breast meat of broiler chickens enlarged to the detriment of the PUFA fraction. PUFA are responsible for various functions in the body and are precursors of cellular functions molecules (Abdulla et al., 2019). *T. molitor* oil supplementation increased n-3 and n-6 fatty acids in breast meat of chickens (Benzertiha et al., 2019a). On the contrary, MUFA fraction was unaffected (Schiavone et al., 2017). It seems that insect meals used in broiler chickens have the potential to produce meat with comparable chemical traits compared to those fed diets containing traditional feed ingredients (Pieterse et al., 2019).

From physical meat properties, the pH value is important for the detection of meat defects like PSE (pale, soft, exudative meat) if the pH value measured 15 minutes *post mortem* is lower than 5.6. Cullere et al. (2016) obtained that quails fed *H. illucens* at 10 or 15% had a pH value of around 5.67, that is slightly lower than in control group fed soy-based diet. On the other hand, according to the study of Bovera et al. (2016), poultry fed with insect meals had higher pH value. In contrast, Pieterse et al. (2019) showed that no treatment differences were found regarding to the initial and ultimate pH of the thigh muscles. Despite this, the addition of insect meals did not lead to negative changes in pH values that could indicate meat defects.

Nutrition can also affect meat colour, as it is the main sources of pigments in animal life. Consumers consider meat colour an important quality clue at the point of purchase (Fletcher, 1999). Secci et al. (2018) have recently found that 1 kg of *H. illucens* larval meal contained around 42 g of total tocopherols and 2 mg of total carotenoids. The pigments in animal feeding are derived from all the ingredients utilized for the formulation. No significant treatment differences for colour were observed regarding the colour characteristics of the broiler breast muscle (Fletcher, 1999). Secci et al. (2018) did not find any differences in meat colour parameters between barbary partridge fed with soybean meal, insect meals or vegetable oils.

Another meat quality parameter important for the consumer is meat tenderness, which was not affected by the introduction of insect meals in the diet (Bovera et al., 2016; Pieterse et al., 2019). Water holding capacity of meat can be described by the drip loss or cooking loss when the meat is heat-treated. Drip loss was the lowest for the larvae-fed samples compared to those with soybean (Pieterse et al., 2014). However, when meat was heat-treated poultry fed with insect meals had higher cooking losses

(Bovera et al., 2016). In another study, no significant treatment differences were found for thaw loss and cooking loss (Pieterse et al., 2019).

Broilers are monogastric animals, any variation in the chemical composition of the feeds could potentially influence (positively or negatively) the sensory profile of the meat (Pieterse et al., 2019). According to the study of Hwangbo et al. (2009), the organoleptic characteristics of broiler meat were not affected by insect meals in the diet. Likewise, the sensory test of Onsongo et al. (2018) suggests that inclusion of *H. illucens* meal in broiler diets does not affect consumer preference for broiler chicken breast meat consumption because the insect meals inclusion did not change the taste and aroma of the meat as well as in study of Pieterse et al. (2019).

On the other hand, fresh chicken breast filets score had the most intensive flavour in *H. illucens* fed group (Altmann et al., 2018). The larvae-fed meat samples scored significantly higher for sustained juiciness compared to the soy and fish meal-fed samples and it also provides an indication that broilers fed larvae meal could have juicier meat (Pieterse et al., 2014).

Therefore, it can be concluded that the substitution of soy-based protein with insect meals expressed very modest or no changes in the meat quality for many of the meat quality parameters.

SAFETY

Safety aspects of insects for feed production are not well-known until now. Insects can receive certain substances from the feed or growing substrate. Goumperis (2012) reported potential hazards of insects for feed production. Feed for insects can be contaminated with mycotoxins, heavy metals, pesticides etc. (Van der Spiegel et al., 2013). Mycotoxins from feed or substrate for insects rearing can affect the growth, inhibit larval development or increase mortality of insects. Consumption of mycotoxin-contaminated insect can present a risk to animals. However, Schrogel & Wätjen (2019) reviewed the effect of mycotoxins on insect safety. These authors showed that no accumulation of various mycotoxin concentration was observed in different feeding experiments with various insect species; even up, the mycotoxin concentration in substrate was 25-times more than maximum limit. According to results, it is better to starve insect of at least 24 hours before harvesting to eliminate mycotoxins in the insect's body.

Toxicity of heavy metals (e.g., cadmium, arsenic, cobalt, copper, nickel etc.) is due to interference with vital cellular components. Vijver et al. (2003) showed upon the update and accumulation of heavy metals (cadmium, copper, lead, zinc) from soil by *T. molitor* larvae. If the level of contaminants were very low, no additional hazard to animals or animal products was expected (Schrogel &Wätjen, 2019). According to the review of these authors, *H. illucens* is capable to accumulate cadmium and *T. molitor* accumulates arsenic. Diener et al. (2015) showed that the insect larvae could accumulate some heavy metals in their body, such as cadmium or plumbum immobilized in the exoskeleton. Accumulation of heavy metals occurred to varying outspread dependent on metal type, insect species and its stages. The contamination is especially for the insect adults which eats grass.

Potential risk of the insects themselves can be allergens, pesticides, contaminant or pathogens (Van der Spiegel et al., 2013). Insects also contained chemical defence substances as toxins produced by the exocrine gland. The presence of pathogenic microorganisms in insects used as feed or its constituent presents a potential health risk that can be prevented by farming or processing conditions (Rumpold & Schlüter, 2013). The prevention of these risks is rearing insects on pollutant-free substrate.

On the other hand, Jin et al. (2016) did not detect the effect of mealworm on blood IgG and IgA concentration as an immune response. Benzertiha et al. (2019b) showed that the small amount of *T. molitor* and *Z. morio* (0.2 and 0.3%) full-fat meals to the diet of broiler chickens decreased the levels of IgM and IgY and may have a significant effect on the immune response. According to these authors, the antimicrobial effects of insect components such as chitin and antimicrobial peptides could explain this effect. Belluco et al. (2013) showed that insects have no additional hazards compared to usually consumed animal products. Likewise, *T. molitor* meal inclusion did not impair the blood parameters, which verifies the safety of insect meals inclusion in poultry diet (Bovera et al., 2015; Biasato et al., 2018a).

CONCLUSIONS

Overall, the literature reviews verify that insect meals contain sufficient nutrients for broiler production and have no negative effect on most of carcass and meat characteristics. Insect meals can be suitable alternative protein source for the feeding of chickens. However, in the European Union, the insect meals are defined as processed animal protein and its utilization in livestock nutrition is banned.

If the feeding will be allowed, the limited quantity of produced insects could be a significant obstacle. Likewise, the prices for insect meals are presently high and it is necessary to develop automated process technologies for rearing and harvesting (Rumpold & Schlüter, 2013; Józefiak et al., 2016). Therefore, further research is needed to maintain safety and good technological practices for the possible production of insects as a source for poultry feed.

ACKNOWLEDGEMENT. The study was supported by the Ministry of Agriculture of the Czech Republic (Project NAAR No. QK1910387).

REFERENCES

Abdulla, N.R., Loh, T.C., Foo, H.L., Alshelmani, M.I. & Akit, H. 2019. Influence of Dietary Ratios of n-6: n-3 Fatty Acid on Gene Expression, Fatty Acid Profile in Liver and Breast Muscle Tissues, Serum Lipid Profile, and Immunoglobulin in Broiler Chickens. *J. Appl. Poultry Res.* **28**, 454–469.

Altmann, B.A., Neumann, C., Velten, S., Liebert, F. & Mörlein, D. 2018. Meat quality derived from high inclusion of a micro-alga or insect meal as an alternative protein source in poultry diets: a pilot study. *Foods Basel Switz.* **7**, 34.

Al-Qazzaz, M.F.A., Ismail, D., Akit, H. & Idris, L.H. 2016. Effect of using insect larvae meal as a complete protein source on quality and productivity characteristics of laying hens. *R. Bras. Zootec.* **45**, 518–523.

Awoniyi, T., Aletor, V. & Aina, J. 2003. Performance of broiler-chickens fed on maggot meal in place of fishmeal. *Int. J. Poult. Sci.* **2**, 271–274.

Ballitoc, D.A. & Sun, S. 2013. Ground yellow mealworms (*Tenebrio molitor* L.) feed supplementation improves growth performance and carcass yield characteristics in broilers. *Open Sci. Reposit.* Agric. doi: 10.7392/openaccess.23050425

Barker, D., Fitzpatrick, M.P. & Dierenfeld, E.S. 1998. Nutrient composition of selected whole invertebrates. *Zoo Biology* **17**, 123–134.

Belluco, S., Losasso, C., Maggioletti, M., Alonzi, C.C., Paoletti, M.G. & Ricci, A. 2013. Edible insects in a food safety and nutritional perspective: A critical review. *Compr. Rev. Food Sci. F.* **12**, 296–313.

Benhabiles, M.S, Salah, R., Lounici, H., Drouiche, N., Goosen, M.F.A & Mameri, N. 2012. Antibacterial activity of chitin, chitosan and its oligomers prepared from shrimp shell waste. *Food hydr.* **29**, 48–56.

Benzertiha, A., Kierończyk, B., Rawski, M., Kołodziejski, P., Bryszak, M. & Józefiak, D. 2019a. Insect oil as an alternative to palm oil and poultry fat in broiler chicken nutrition. *Animals.* **9**, 116.

Benzertiha, A., Kierończyk, B., Kołodziejski, P., Pruszyńska-Oszmałek, E., Rawski, M., Józefiak, D. & Józefiak, A. 2019b. *Tenebrio molitor* and *Zophobas morio* full fat meals as functional feed aditives affect broiler chickens growth performance and immune system traits. *Poult. Sci.* **0**, 1–11.

Biasato, I., De Marco, M., Rotolo, L., Renna, M., Dabbou, S., Capucchio, M.T., Biasibetti, E., Costa, P., Gai, F., Pozzo, L., Dezzuttto, D., Bergagna, S., Martinez, S., Tarantola, M., Gasco, L. & Schiavone, A. 2016. Effects of dietary Tenebrio molitor meal inclusion in free-range chickens. *J. Anim. Physiol. Anim. Nutr.* **100**, 1104–1112.

Biasato, I., Gasco, L., De Marco, M., Renna, M., Rotolo, L., Dabbou, S., Capucchio, M.T., Biasibetti, E., Tarantola, M., Sterpone, L., Cavallarin, L., Gai, F., Pozzo, L., Bergagna, S., Dezzutto, D., Zoccarato, I. & Schiavone, A. 2018a. Yellow mealworm larvae (Tenebrio molitor) inclusion in diets for male broiler chickens: Effects on growth performance, gut morphology, and histological findings. *Poult. Sci.* **97**, 540–548.

Biasato, I., Ferrocino, I., Biasibetti, E., Grego, E., Dabbou, S., Sereno, A., Gai, F., Gasco, L., Schiavone, A., Cocolin, L. & Capucchio, M.T. 2018b. Modulation of intestinal microbiota, morphology and mucin composition by dietary insect meal inclusion in free-range chickens. *BMC Vet. Res.* **14**, 383.

Borrelli, L., Coretti, L., Dipineto, L., Bovera, F., Menna, F., Chiariotti, L., Nizza, A., Lembo, F. & Fioretti, A. 2017. Insect-based diet, a promising nutritional source, modulates gut microbiota composition and SCFAs production in laying hens. *Sci. Rep.* **7**, 16269.

Bovera, F., Loponte, R., Marono, S., Piccolo, G., Parisi, G., Iaconisi, V., Gasco, L. & Nizza, A. 2016. Use of *Tenebrio molitor* larvae meal as protein source in broiler diet: Effect on growth performance, nutrient digestibility, and carcass and meat traits. *J. Anim. Sci.* **94**, 639–647.

Bovera, F., Piccolo, G., Gasco, L., Marono, S., Loponte, R., Vassalotti, G., Mastellone, V., Lombardi, P., Attia, Y.A. & Nizza, A. 2015. Yellow mealworm larvae (*Tenebrio molitor*, L.) as a possible alternative to soybean meal in broiler diets. *Brit. Poultry Sci.* **56**, 569–575.

Bovera, F., Marono, S., Di Meo, C., Piccolo, G., Iannaccone, F. & Nizza, A. 2010. Effect of mannanoligosaccharides supplementation on caecal microbial activity of rabbits. *Animal* **4**, 1522–1527.

Cullere, M., Tasoniero, G., Giaccone, V., Miotti-Scapin, R., Claeys, E., De Smet, S. & Dalle Zotte, A. 2016. Black soldier fly as dietary protein source for broiler quails: Apparent digestibility, excreta microbial load, feed choice, performance, carcass and meat traits. *Animal* **10**, 1923–1930.

Cutrignelli, M.A., Messina, M., Tulli, F., Randazzo, B., Olivotto, I., Gasco, L., Loponte, R., Bovera, F. 2018. Evaluation of an insect meal of the black soldier fly (*Hermetia illucens)* as soybean substitute: Intestinal morphometry, enzymatic and microbial acivity in laying hens. *Res. Vet. Sci.* **117**, 209–215.

De Foliart, G.R. 1991. Insect atty acids: similar to those or poultry and fish in their degree of unsaturation but higher in the polyunsaturates. *Food Insects. Newsl.* **4**, 1–4.

De Marco, M., Martínez, S., Hernandez, F., Madrid, J., Gai, F., Rotolo, L., Belforti, M. Bergero, D., Katz, H., Dabbou, S., Kovitvadhi, A., Zoccarato, I., Gasco, L. & Schiavone, A. 2015. Nutritional value of two insect larval meals (Tenebrio molitor and Hermetia illucens) for broiler chickens: Apparent nutrient digestibility, apparent ileal amino acid digestibility and apparent metabolizable energy. *Anim. Feed Sci. Technol.* **209**, 211–218.
Diener, S., Zurbrügg, C. & Tockner, K. 2015. Bioaccumulation of heavy metals in the black soldier fly, *Hermetia illucens* and effects on its life cycle. *J. Insects Food Feed.* **1**, 261–270.
FEFAC. 2012. *Environment report*. 2nd ed. Bruxeles, Belgique, 36 pp.
Finke, M.D. 2002. Complete nutrient composition of commercially raised invertebrates used as food for insectivores. *Zoo Biol.* **21**, 269–285.
Fletcher, D. 1999. Broiler breast meat color variation, pH, and texture. *Poult. Sci.* **78**, 1323–1327.
Forder, R.E., Howarth, G.S., Tivey, D.R. & Hughes, R.J. 2007. Bacterial modulation of small intestinal goblet cells and mucin composition during early posthatch development of poultry. *Poult. Sci.* **86**, 2396–2403.
Forstner, G. & Forstner, J.F. 1994. Gastrointestinal mucus. In: Johnson, L.R., editor. *Physiology of the gastrointestinal tract.* Raven Press, New York, pp. 1255–1284.
Ghaly, A.E. & Alkoaik, F.N. 2009. The yellow mealworms as a novel source of protein. *Am. J. Agric. Biol. Sci.* **4**, 319–331.
Goumperis, T. 2012. Insects and food security: food/feed safety considerations. Assessing the potential of insects as food and feed in assuring food security. *Technical Consultation Meeting*, 23–25 January 2012. Rome: FAO.
Henry, M., Gasco, L., Piccolo, G. & Fountoulaki, E. 2015. Review on the use of insects in the diet of farmed fish: past and future. *Anim. Feed Sci. Technol.* **203**, 1–22.
Hwangbo, J., Hong, E., Jang, A., Kang, H., Oh, J., Kim, B. & Park, B.S. 2009. Utilization of house fly-maggots, a feed supplement in the production of broiler chickens. *J. Environ. Biol.* **30**, 609–614.
Janssen, R.H., Vincken, J.P., van den Broek, L.A.M., Fogliano, V. & Lakemond, K.M.M. 2017. Nitrogen-to-protein conversion factor for three edible insects: *Tenebrio molitor, Alphitobius diaperinus.* And *Hermetia illucens. J. Agric. Food Chem.* **65**, 2275–2278.
Jenkins, A.P. & Thompson, R.P.H. 1993. Does the fatty-acid profile of dietary-Fat influence its trophic effect on the small intestinal mucosa. *Gut*. **34**, 358–364.
Jin, X.H., Heo, P.S., Hong, J.S., Kim, N.J. & Kim, Y.Y. 2016. Supplementation of Dried Mealworm (Tenebrio molitor larva) on Growth Performance, Nutrient Digestibility and Blood Profiles in Weaning Pigs. *Asian-Australas. J. Anim. Sci.* **29**, 979–986.
Johnson, G.D. & Boyce, M.S. 1990. Feeding trials with insects in the diet of sage grouse chicks. *J. Wild. Manage.* **54**, 89–91.
Józefiak, D. & Engberg, R.M. 2015. Insects as poultry feed. In: *Proc. 20th European Symposium on Poultry Nutrition*. Prague, Czech Republic, pp. 73–80.
Józefiak, D., Józefiak, A., Kierończyk, B., Rawski, M., Świątkiewicz, S., Długosz, J. & Engberg, R.M. 2016. Insects – A natural nutrient source for poultry – A review. *Ann. Anim. Sci*. **6**, 297–313.
Józefiak, A. & Engberg, R.M. 2017. Insect proteins as a potential source of antimicrobial peptides in livestock production. *J. Anim. Feed Sci.* **26**, 87–99.
Józefiak, A., Kierończyk, B., Rawski, M., Mazurkiewicz, J., Benzertiha, A., Gobbi, P., Nogales-Mérida, S., Światkiewicz, S. & Józefiak, D. 2018. Full-fat insect meals as feed additive – the effect on broiler chicken growth performance and gastrointestinal tract microbiota. *J. Anim. Feed Sci.* **27**, 131–139.
Józefiak, A., Nogales-Mérida, S., Mikołajczak, Z., Rawski, M., Kierończyk, B., Mazurkiewicz, J. 2019. The utilization of full-fat insect meal in rainbow trout (*Oncorhynchus mykiss)* nutrition: the effects on growth performance, intestinal microbiota and gastrointestinal tract histomorphology. *Ann. Anim. Sci.* **19**, 747–765.

Kareem, K.Y., Abdulla, N.R., Foo, H.L., Mohd, A.N., Zamri, N.S., Loh, T.C. & Alshelmani, M.I. 2018. Effect of feeding larvae meal in the diets on growth performance, nutrient digestibility and meat quality in broiler chicken. *Indian J. Anim. Sci.* **88**, 1180–1185.

Khan, S., Khan, R.U., Sultan, A., Khan, M., Hayat, S.U. & Shahid, M.S. 2016. Evaluating the suitability of maggot meal as a partial substitute of soya bean on the productive traits, digestibility indices and organoleptic properties of broiler meat. *J. Anim. Physiol. An. N.* **100**, 649–656.

Khan, M., Chand, N., Khan, S., Khan, R.U. & Sultan, A. 2018. Utilizing the house fly (Musca Domestica) larva as an alternative to soybean meal in broiler ration during the starter phase. *Braz. J. Poult. Sci.* **20**, 9–14.

Khempaka, S., Chitsatchapong, C. & Molee, W. 2011. Effect of chitin and protein constituents in shrimp head meal on growth performance, nutrient digestibility, intestinal microbial populations, volatile fatty acids, and ammonia production in broilers. *J. Appl. Poult. Res.* 20, 1–11.

Khoushab, F. & Yamabhai, M. 2010. Chitin Research Revisited. *Mar. Drugs.* **8**, 1988–2012.

Khusro, M., Andrew, N.R. & Nicholas, A. 2012. Insects as poultry feed: a scoping study for poultry production systems in Australia. *World Poult. Sci. J.* **68**, 435–446.

Kierończyk, B., Rawski, M., Józefiak, A., Mazurkiewicz, J., Swiatkiewicz, S., Siwek, M., Bednarczyk, M., Szumacher-Strabel, M., Cieslak, A., Benzertiha, A. & Józefiak, D. 2018. Effects of replacing soybean oil with selected insect fats on broilers. *Anim. Feed Sci. Technol.* **240**, 170–183.

Kierończyk, B., Sypniewski, J., Rawski, M., Czekala, W., Światkiewicz, S. & Józefiak, D. 2020. From waste to sustainable feed material: the effect of *Hermetia illucens* oil on the growth performance, nutrient digestibility, and gastrointestinal tract morphometry of broiler chickens. *Ann. Anim. Sci.* doi: 10.2478/aoas-2019-0066

Kramer, K.J., Hopkins, T.L. & Schaefer, J. 1995. Applications of solids NMR to the analysis of insect sclerotized structures. *Insect Biochem. Mol. Biol.* **25**, 1067–1080.

Laudadio, V., Passantino, L., Perillo, A., Loprestu, G., Passantino, A., Khan, R.U. & Tufarelli, V. 2012. Productive performance and histological features of intestinal mucosa of broiler chickens fed different dietary protein levels. *Poult. Sci.* **91**, 265–270.

Lee, H.W., Park, Y.S., Jung, J.S. & Shin, W.S. 2002. Chitosan oligosaccharides, dp 2-8, have prebiotic effect on the *Bifidobacterium bifidum* and *Lactobacillus* sp. *Food Microbiol.* **8**, 319–324.

Leiber, F., Gelencsér, T., Stamer, A., Amsler, Z., Wohlfahrt, J., Früh, B. & Maurer, V. 2017. Insect and legume-based protein sources to replace soybean cake in an organic broiler diet: Effects on growth performance and physical meat quality. *Renew. Agr. Food Sys.* **32**, 21–27.

Liu, N., Abe, M., Sabin, L.R., Hendriks, G.J., Nagvi, A.S., Yu, Z., Cherry, S. & Bonini, N.M. 2011. The exoribonuclease Nibbler controls 3′ end processing of microRNAs in *Drosophila*. *Curr. Biol.* **21**, 1888–1893.

Loponte, R., Nizza, S., Bovera, F., Riu De, N., Fliegerova, K., Lombardi, P., Vassalotti, G., Mastellone, V., Nizza, A. & Moniello, G. 2017. Growth performance, blood profiles and carcass traits of barbary partridge (Alectoris barbara) fed two different insect larvae meals (Tenebrio molitor and Hermetia illucens). *Res.Vet. Sci.* **115**, 183–188.

Makkar, H.P., Tran, G., Heuzé, V. & Ankers, P. 2014. State-of-the-art on use of insects as animal feed. *Anim. Feed Sci.Technol.* **197**, 1–33.

Moula, N., Scippo, M.L., Douny, C., Degand, G., Dawans, E., Cabaraux, J.F., Hornick, J.L., Medigo, R.C., Leroy, P., Francis, F. & Detilleux, J. 2017. Performances of local poultry breed fed black soldier fly larvae reared on horse manure. *Anim. Nutr.* **4**, 73–78.

Nguyen, T.T.X., Tomberlin, J.K. & Vanlaerhoven, S. 2015. Ability of Black Soldier Fly (Diptera: Stratiomyidae) Larvae to recycle food waste. *Environ Entomol.* 44, 407–410.

Onsongo, V.O., Osuga, I.M., Gachuiri, C.K., Wachira, A.M., Miano, D.M., Tanga, C.M., Ekesi, S., Nakimbugwe, D. & Fiaboe, K.K.M. 2018. Insects for income generation through animal feed: effect of dietary replacement of soybean and fish meal with black soldier fly meal on broiler growth and economic performance. *J. Econ. Entomol.* **111**, 1966–1973.

Özek, K., Yazgan, O. & Bahtiyarca, Y. 2003. Effects of dietary protein and energy concentrations on performance and carcass characteristics of Chukar Partridges (*Alectoris chukar*) raised in captivity. *Brit. Poultry Sci.* **3**, 419–426.

Pieterse, E., Erasmus, S.W., Uushona, T. & Hoffman, L.C. 2019. Black soldier fly (*Hermetia illucens*) pre-pupae meal as a dietary protein source for broiler production ensures a tasty chicken with standard meat quality for every pot. *J. Sci. Food Agric.* **99**, 893–903.

Pieterse, E., Pretorius, Q., Hoffman, L.C. & Drew, D. 2014. The carcass quality, meat quality and sensory characteristics of broilers raised on diets containing either *Musca domestica* larvae meal, fish meal or soya bean meal as the main protein source. *Anim. Prod. Sci.* **54**, 622–628.

Poorghasemi, M., Seidavi, A., Qotbi, A.A., Laudadio, V. & Tufarelli, V. 2013. Influence of dietary fat source on growth performance responses and carcass traits of broiler chicks. *Asian-Australas. J. Anim. Sci.* **26**, 705–710.

Pretorius, Q. 2011. *The evaluation of larvae of Musca domestica (common house fly) as protein source for broiler production*, Doctoral dissertation, Stellenbosch University. 95 pp.

Ramos-Elorduy, J. 2005. Insects: a hopeful food source. In M.G. Paoletti, ed. *Ecological implications of minilivestock*. Science Pub., Enfield NH, USA pp. 263–291.

Ramos-Elorduy, J., Gonzalez, E.A., Hernandez, A.R. & Pino, J.M. 2002. Use of Tenebrio molitor (Coleoptera: *Tenebrionidae*) to recycle organic wastes and as feed for broiler chickens. *J. Econ. Entomol*. **95**, 214–220.

Rumpold, B.A. & Schlüter, O.K. 2013. Potential and challenges of insects as an innovative source for food and feed production. Innov. *Food Sci. Emerg. Technol.* **17**, 1–11.

Sánchez-Muros, M.J., Barroso, F.G. & Manzano-Agugliaro, F. 2014. Insect meal as renewable source of food for animal feeding: A review. *J. Clean. Prod.* **65**, 16– 27.

Schiavone, A., De Marco, M., Rotolo, L., Belforti, M., Martinez Mirò, S., Madrid Sanchez, J., Hernandez Ruiperez, F., Bianchi, C., Sterpone, L., Malfatto, V., Katz, H., Zoccarato, I., Gai, F. & Gasco, L. 2014. Nutrient digestibility of Hermetia illucens and Tenebrio molitor meal in broiler chickens. In: Proc. *Conference Insects to Feed The World, Abstract Book*. Netherlands, pp. 84.

Schiavone, A., Cullere, M., De Marco, M., Meneguez, M., Biasato, I., Bergagna, S., Dezzutto, D., Gai, F., Dabbou, S., Gasco, L. & Dalle Zotte, A. 2017. Partial or total replacement of soybean oil by black soldier fly larvae (Hermetia illucens L.) fat in broiler diets: Effect on growth performances, feed-choice, blood traits, carcass characteristics and meat quality. *Ital. J. Anim. Sci.* **16**, 93–100.

Schiavone, A., Dabbou, S., De Marco, M., Cullere, M., Biasato, I., Biasibetti, E., Capucchio, M.T., Bergagna, S., Dezzutto, D., Meneguz, M., Gai, F., Dalle Zotte, A. & Gasco, L. 2018. Black soldier fly larva fat inclusion in finisher broiler chicken diet as an alternative fat source. *Animal*. **12**, 2032–2039.

Schrogel, P. & Wätjen, W. 2019. Insects for food and feed-safety aspects related to mycotoxins and metals. *Foods*. **8**, 288.

Secci, G., Bovera, F., Nizza, S. & Baronti, N. 2018. Quality of eggs from Lohmann Brown classic laying hens fed black soldier fly meal as substitute for soya bean. *Animal* **8**, 1–7.

Song, Y.S., Kim, M.W., Moon, C., Seo, D.J., Han, Y.S., Jo, Y.H., Noh, M.Y., Park, Y.K., Kim, S.A., Kim Y.W. & Jung, W.J. 2018. Extraction of chitin and chitosan from larval exuvium and whole body of edible mealworm, *Tenebrio molitor*. *Entomol. Res.* **48**, 227–233.

Spranghers, T., Ottoboni, M., Klootwijk, C., Ovyn, A., Deboosere, S., De Meulenaer, B., Michiels, J., Eeckhout, M., De Clercq, P. & De Smet, S. 2017. Nutritional composition of black soldier fly (Hermetia illucens) prepupae reared on different organic waste substrates. *J. Sci. Food. Agric.* **97**, 2594–2600.

Spranghers, T., Michiels, J., Vrancx, J., Ovyn, A., Eeckhout, M., De Clercq, P. & De Smet, S. 2018. Gut antimicrobial effects and nutritional value of black soldier fly (*Hermetia illucens* L.) prepupae for weaned piglets. *Anim. Feed Sci. Technol.* **235**, 33–42.

Stamer, A. 2015. Insect proteins – a new source for animal feed. *Embo Reports* **16**, 678–680.

Surendra, K.C., Olivier, R., Tomberlin, J.K., Jha, R. & Khanal, S.K. 2016. Bioconversion of organic wastes into biodiesel and animal feed via insect farming. *Renew Energy* **98**, 197–202.

Suzuki, M., Fujimoto, W., Goto, M., Morimatsu, M., Syuto, B. & Toshihiko, I. 2002. Cellular expression of gut chitinase mRNA in the gastrointestinal tract of mice and chickens. *J. Histochem. Cytochem.* **50**, 1081–1089.

Tabata, E., Kashimura, A., Wakita, S., Ohno, M., Sakaguchi, M., Sugahara, Y., Kino, Y., Matoska, V., Bauer, P.O. & Oyama, F. 2017. Gastric and intestinal proteases resistance of chicken acidic chitinase nominates chitin-containing organisms for alternative whole edible diets for poultry. *Sci. Rep.* **7**, 6662.

Tancharoenrat, P., Ravindran, V., Zaefarian, F. & Ravindran, G. 2014. Digestion of fat and fatty acids along the gastrointestinal tract of broiler chickens. *Poult Sci.* **93**, 371–379.

Tran, G., Heuzé, V. & Makkar, H.P.S. 2015. Insects in fish diets. *Animal Frontiers* **5**, 37–44.

Tschirner, M. & Simon, A. 2015. Influence of different growing substrates and processing on the nutrient composition of black soldier fly larvae destined for animal feed. *J. Insects Food Feed.* **1**, 249–259.

Van der Spiegel, M., Noordam, M.Y. & Van der Fels-Klerx, H.J. 2013. Safety of novel protein sources (insects, microalgae, seaweed, duckweed, and rapeseed) and legislative aspects for their application in food and feed production. *Compr. Rev. Food Sci. F.* **12**, 662–678.

Van Huis, A., van Itterbeeck, J., Van Klunder, H., Mertens, E., Halloran, A. & Muir, G. 2013. *Edible insects. Future prospects for food and feed security.* Forestry paper 171. Food and Agriculture Organization, Rome, 187 pp.

Verbeke, W. 2015. Profiling consumers who are ready to adopt insects as a meat substitute in a Western society. *Food Qual. Prefer.* **39**, 147-155.

Vijver, M., Jager, T., Posthuma, L. & Peijnenburg, W. 2003. Metal uptake from soils and soil–sediment mixtures by larvae of *Tenebrio molitor* (L.) (Coleoptera). *Ecotoxicol. Environ. Safety* **54**, 277–289.

Woods, M.J., Cullere, M., Van Emmenes, L., Vincenzi, S., Pieterse, E., Hoffman, L.C. & Zotte, A.D. 2019. Hermetia illucens larvae reared on different substrates in broiler quail diets: effect on apparent digestibility, feed-choice and growth performance. *J. Insect. Food Feed* **5**, 89–98.

Zeitz, J., Fennhoff, O.J., Kluge, H., Stangl, G.I. & Eder, K. 2015. Effects of dietary fats rich in lauric and myristic acid on performance, intestinal morphology, gut microbes, and meat quality in broilers. *Poultry Sci.* **94**, 2404–2413.