



Review Article

Available for millions of years but discovered through the last decade: Insects as a source of nutrients and energy in animal diets



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ABSTRACT

The aim of this review is to present and discuss the most recent literature about the processing of insect biomass and its impact on nutritive value, further implementation of meals and fats derived from invertebrates to livestock (poultry and swine), aquaculture (salmonids), and companion animal diets and their impact on growth performance, metabolic response, and gastrointestinal microbiota shifts. Additionally, the most important barriers to obtaining unified products in terms of their nutritive value are considered, i.e., to define insects' nutrient requirements, including various technological groups and further biomass processing (slaughtering, drying, and storage). Due to the current limitation in the insect production process consisting of the lack of infrastructure, there is stress on the relatively small amount of insect products added to the animal diets as a functional feed additive. Currently, only in the case of pet nutrition may insects be considered a full replacement for commonly used environmentally harmful and allergenic products. Simultaneously, the least information has been published on this topic. Thus, more scientific data are needed, particularly when the pet food branch and insect-based diets are rapidly growing.

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1. Introduction

Insect biomass is stated as a new alternative source of nutrients for various animal species. However, we should post the question of whether this is a real alternative or rather a natural choice for modern birds or fish present on earth for over 60 million years, which in wild conditions do not have access to soybean meal, fish

meal, or other raw materials that have been developed in recent decades of animal production and nutrition. Furthermore, the production of these commonly used feed materials often causes environmental degradation (deforestation, ocean overharvesting, etc.) or are not accepted by consumers due to their genetic modification. Nonetheless, insect usage as the main protein source has been frequently published in the available literature (Allegretti et al., 2018; El-Hack et al., 2020; Józefiak et al., 2016; Kim et al., 2019). Thus, in the present review, the continuation of invertebrate administration as a substituent for commonly used and environmentally harmful ingredients such as soybean meal or fish meal was not deliberated. Based on the PubMed database (pubmed.ncbi.nlm.nih.gov), there is clearly shown that the last decade was the most intensive period for exploring the field of insect usage as a meal (Fig. 1A). Furthermore, in the scope of 2 insect species that are the most economically justified from the practical point of view, i.e.,

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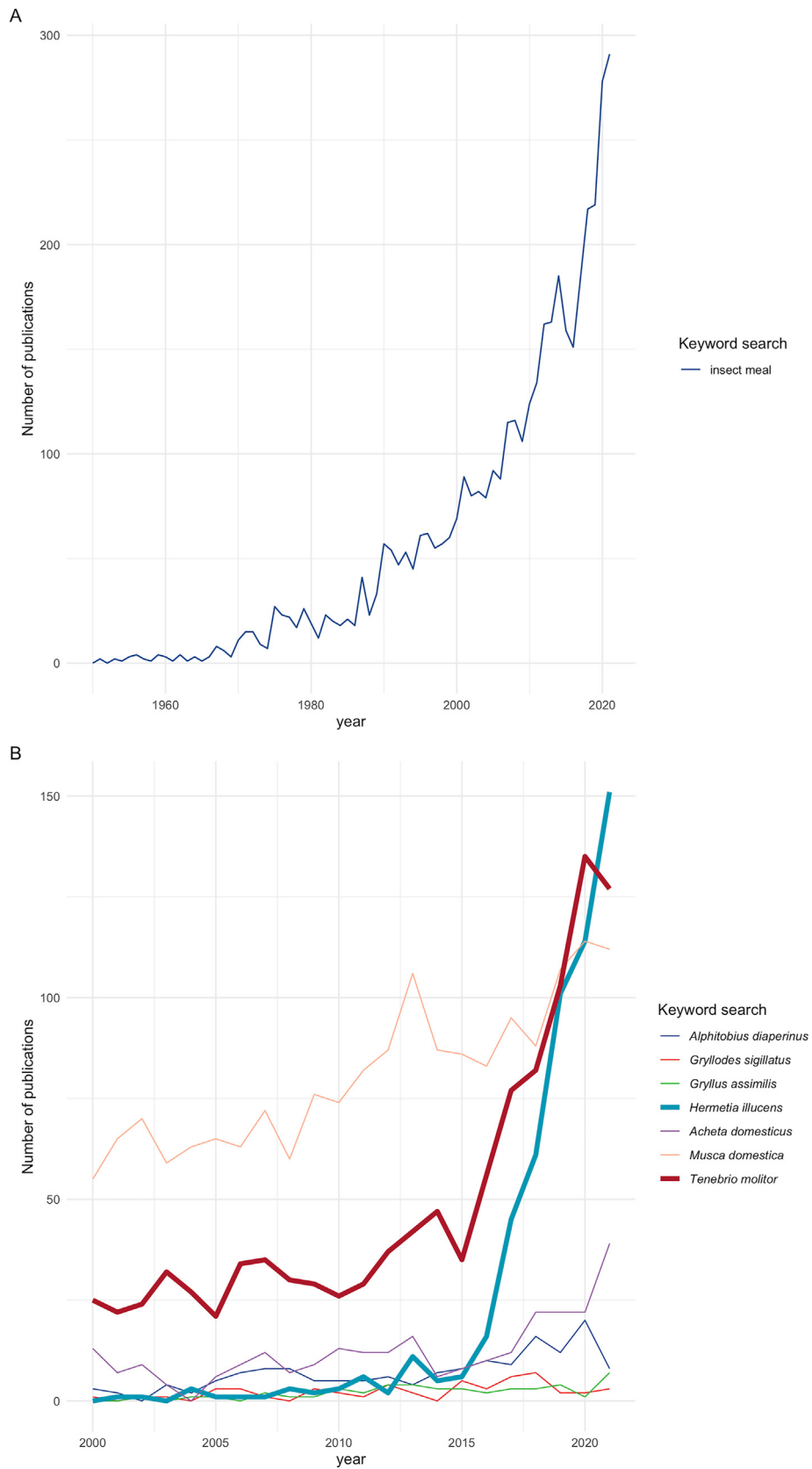


Fig. 1. Frequency of the scientific articles publishing based on PubMed database using the following keywords: (A) “insect meal”, or (B) the name of species considered as livestock by the EU Commission. The bolded lines were used to emphasize the 2 most profitable insect species (*Hermetia illucens* and *Tenebrio monitor*).

Hermetia illucens and *Tenebrio molitor*, the largest growth in the number of articles published in scientific journals is observed in the last 5 years (Fig. 1B). The abovementioned trend is connected to the recent development of the insect meal producer market, not only in Asia or North America but also in Europe, where in general the usage of invertebrates in the animal and human diet was forgotten. However, it should be emphasized that the limitation of invertebrate biomass production and application under field conditions is currently caused by 1) developing technology for invertebrate production; 2) processing of the invertebrate biomass for animal nutrition; 3) limited infrastructure availability; 4) the lack of systemic solutions for the distribution and collection of food wastes; 5) no nutrient requirements for invertebrates; and finally, 6) high variability in biomass nutritive value. Nonetheless, the infrastructure (production scaling up) seems to be the most important bottleneck of the insect farming industry, and consequently, there is no possibility of commonly administered invertebrate protein in animal diets, e.g., poultry at the suggested level, i.e., up to 20% (de Souza Vilela et al., 2021). Additionally, the price per tonne of insect product is not acceptable in intensive rearing conditions of livestock, where 70% of all production costs are connected with nutrition. Based on the latest statistics by the European Feed Manufacturers Federation (FEFAC), compound feed only for poultry was produced by the EU-28 in 2019 at the level of approximately 56 million tonnes and was 9% higher than its production in 2013 (EU-28) (FEFAC.eu). Hence, 1% replacement of feed using insect meals needs to be produced, e.g., 1.68 million tonnes live black soldier fly larvae (BSFL; *H. illucens*). In contrast, insect market production by 2030 is estimated to be 250 thousand tonnes of invertebrate products, including whole dry insects and incorporated ingredients (IPIFF.org).

The introduction of novel feedstuffs requires many optimizations in terms of quality, availability, and supply chains. Therefore, the mass production of insects for livestock or companion animal nutrition should be at a consistent level and quality, which enforces different actions during insect rearing and processing. In this respect, one of the most important impediments of insect biomass implementation to animal nutrition is enormous nutritive value variability (Table 1). It is well documented that the chemical composition of insects is species (Janssen et al., 2017), development stage and sex (Liu et al., 2017), diet composition (Adebayo et al., 2021), and processing technique dependent (Huang et al., 2019). Nonetheless, the nutrition of larvae seems to be the most crucial to modulate the nutritive value of the final biomass. Therefore, the aim of this review is to focus not only on the application of insect-based raw materials in animal nutrition but also on an overview of various factors that affect their further nutritive value.

2. Insect nutrition

In the available literature, the usage of manure, sludge, slaughterhouse wastes, or catering waste as a rearing substrate has been frequently studied (Gold et al., 2020; Lalander et al., 2019; Rehman et al., 2019). However, in the European Union, due to the definition of the selected insect species, i.e., *H. illucens* (black soldier fly), *T. molitor* (yellow mealworm), *Musca domestica* (common housefly), *Alphitobius diaperinus* (lesser mealworm), *Acheta domesticus* (house cricket), *Grylloides sigillatus* (banded cricket), and *Gryllus assimilis* (field cricket), as livestock by the European Parliament and the Council, does currently not allow to feed invertebrates using the abovementioned materials (EC No 178/2002; 852/2004; 183/2005), and it will not be presented in this review. Furthermore, the vast majority of the scientific literature has focused on compound diets such as chicken feed or vegetable wastes, which is not sufficiently informative and may make an

illusory sense of progress in the field of insect nutrition. This is probably due to the high insects' ability to adapt via flexibility of the midgut to wide spectra of various organic materials, particularly *H. illucens*, which is classified as a saprophagous species (Bonelli et al., 2020). It must be emphasized that insects should be fed specific nutrients, not specific feed materials, because they have a specific nutrient requirement. Thus, a permanent evaluation of the nutritive value of feed materials (byproducts of the agri-food industry) during insect rearing is needed. To date, there is scarce information about the impact of dietary macronutrients (crude protein or nitrogen-free extract) on the chemical composition of invertebrates. Some studies have been carried out on the protein-to-carbohydrate ratio (P:C) in the Lepidoptera, Orthoptera, Coleoptera, and Blattodea orders (Behmer, 2009; Raubenheimer and Simpson, 2003; Roeder and Behmer, 2014; Simpson et al., 1988; Waldbauer and Bhattacharya, 1973). Instead, from the authors' point of view, the most stress of further research investigations should be put on recognizing and systemizing the nutrient requirements for economically justified insect species, such as *H. illucens* and *T. molitor*. Cammack and Tomberlin (2017) emphasized that an equal P:C ratio causes the fastest development of *H. illucens* and a beneficial survival rate when the substrate has 30% dry matter (DM), contrary to 5:1 or 1:5 ratios. Furthermore, not only the ratio between nutrients but also their concentration should be taken into consideration. Barragan-Fonseca et al. (2019) noted that development duration, as well as larval and pupal mass, is mostly dependent on protein and carbohydrate levels, >50% and 80%, respectively. The P:C interaction is responsible for approximately 20% of the effect on larval development. This finding is in line with the results of Le Gall and Behmer (2014), who reported that carbohydrates are responsible mainly for the increased biomass of larvae. Nevertheless, in the scope of the chemical composition, the crude protein (CP) content of the obtained *H. illucens* biomass is negatively related to increased concentration in the rearing medium (Barragan-Fonseca et al., 2018, 2019; Beniers and Graham, 2019; Tschirner and Simon, 2015). Simultaneously, the reports of Meneguz et al. (2018) indicated that not only the level but also the quality of protein (fruit wastes vs. brewery byproducts) has a crucial impact on its content in the larvae. Moreover, Barragan-Fonseca et al. (2021) estimated that both the protein and carbohydrate levels equally affected the protein content in the *H. illucens* biomass, while the variation between larval CP concentrations was modulated at the narrow spectrum, i.e., approximately between 41% and 45%. In contrast, the crude fat content varies over a considerable range (approximately 6% to above 30%), and increasing concentrations of protein and carbohydrates in the diet result in high fat levels (Barragan-Fonseca et al., 2019). This result is in agreement with Spranghers et al. (2019), who noted a high correlation ($R^2 = 0.94$) between the sum of carbohydrate and protein levels and larval growth. Furthermore, the results of Beniers and Graham (2019) exclude the hypothesis that carbohydrates may enlarge fat accumulation. It should be highlighted that the abovementioned results stated only the beginning of the construction of the detailed nutrient requirements for selected insect species. Further research is needed to divide the specific nutritional needs for species, developmental stages, parental stocks, and intended biomass usage. Therefore, similar to other animals, insect rearing requires the nutritive value of feedstuffs and the nutrient composition of the diets. The impact of the substrates used in insect rearing is important, but today, it is not clear how their modification can influence final product quality and their usage in animal nutrition. Thus, it is highly recommended to expand the evaluation of the transfer chain of nutrients from rearing substrate to insect biomass in the future as a milestone to create a nutrient requirement for insect biomass production.

Table 1
The nutritive value variability of the selected insect species.¹

Item	<i>Hermetia illucens</i>	<i>Tenebrio molitor</i>	<i>Musca domestica</i>
Dry matter, %	31.4 ± 5.2	54.0 ± 12.8	24.3 ± 0
Crude protein, % DM	43.3 ± 7.1	53.3 ± 7.4	54.1 ± 10.7
Crude fat, % DM	26.3 ± 11.2	29.8 ± 8.7	21.2 ± 6.3
Crude ash, % DM	12.3 ± 7.9	4.2 ± 1.2	10.2 ± 6.8
Chitin, % DM	4.6 ± 1.5	5.9 ± 1.4	ND ± ND
AME _N for poultry, MJ/kg	17.6 ± 3.6	21.7 ± 0	17.3 ± 0
Gross Energy, MJ/kg	24.9 ± 2.9	24.5 ± 2.3	23.1 ± 4.4
Minerals, g/kg DM			
Calcium	27.2 ± 13.7	0.9 ± 0.7	9.8 ± 8.9
Phosphorus	8.9 ± 2.1	7.9 ± 1.5	10.5 ± 2.6
Magnesium	3.6 ± 1.2	2.2 ± 0.6	2.3 ± 0
Potassium	14.7 ± 5.3	9.1 ± 1.0	12.7 ± 0
Sodium	4.1 ± 3.7	1.2 ± 0.5	6 ± 0.9
Chlorine	2.0 ± 0.6	5.7 ± 0	ND ± ND
Sulphur	3.4 ± 1.3	3.5 ± 0	ND ± ND
Manganese, mg/kg DM	214.3 ± 78.5	11.6 ± 3.1	165.0 ± 154.2
Zinc, mg/kg DM	104.2 ± 32.7	110.8 ± 11.2	638.0 ± 567.1
Copper, mg/kg DM	9.4 ± 2.1	16.3 ± 2.9	33.2 ± 1.1
Iron, mg/kg DM	263.1 ± 106.5	70.5 ± 16.9	539.5 ± 91.2
Cobalt, mg/kg DM	0.3 ± 0.3	ND ± ND	ND ± ND
Molybdenum, mg/kg DM	0.9 ± 0.3	ND ± ND	ND ± ND
Amino acids, g/100 g of protein			
Lysine	6.2 ± 0.9	4.6 ± 1.9	6.9 ± 1.5
Threonine	3.9 ± 0.5	3.6 ± 0.9	4.9 ± 1.3
Methionine	1.8 ± 0.4	1.2 ± 0.5	3.8 ± 1.6
Cystine	0.7 ± 0.2	1.4 ± 0.6	1.0 ± 0.3
Tryptophan	1.5 ± 0.4	1.2 ± 0.5	1.4 ± 0.2
Isoleucine	4.3 ± 0.5	4.0 ± 1.3	3.7 ± 1.3
Valine	5.9 ± 0.4	5.3 ± 1.9	4.7 ± 1.8
Leucine	6.9 ± 0.6	6.6 ± 2.3	6.1 ± 0.6
Phenylalanine	4.1 ± 0.9	3.4 ± 1.0	7.1 ± 1.5
Tyrosine	5.9 ± 1.4	5.9 ± 1.5	5.6 ± 1.8
Histidine	3.1 ± 0.8	2.9 ± 1.1	4.0 ± 1.0
Arginine	5.3 ± 1.2	4.5 ± 1.4	6.0 ± 1.6
Aspartic acid	8.9 ± 0.8	7.3 ± 2.2	8.0 ± 2.6
Glutamic acid	11.1 ± 1.2	10.9 ± 3.1	11.8 ± 3.7
Glycine	5.0 ± 0.7	4.8 ± 1.7	3.3 ± 1.6
Serine	4.1 ± 0.3	4.3 ± 1.6	3.9 ± 0.2
Proline	5.4 ± 0.5	5.8 ± 1.87	4.6 ± 0.7
Alanine	6.3 ± 0.8	7.1 ± 2.19	5.0 ± 0.7

AME_N = apparent metabolizable energy corrected to zero nitrogen balance; ND = not detected.

¹ The presented values are based on the literature listed separately in [Supplementary material](#).

Finally, different agroindustry wastes are rich in structural fibers and/or soluble polysaccharides, which may need processing before they are used as substrates for insects. Feed structure, particle size, viscosity, dry matter content, etc., also play an important role in terms of feed distribution and its availability and need further investigation, while not only feed chemical composition but also its physical affect insect performance.

3. Larval biomass processing

In addition to the modulation of insect chemical composition by rearing substrate, there is also a possibility of negatively affecting larval nutritive value through the selection of inadequate biomass processing conditions, i.e., slaughter method, drying process, and storage. The most popular slaughtering methods include heating (desiccation, blanching), freezing, asphyxiation, and usage of mechanical techniques (grinding, high hydrostatic pressures). Among those listed, the blanching technique seems to be favorable because of its positive effect on the limitation of lipid oxidation and reduction of Maillard reaction occurrence (color stability; inactivate phenol oxidase) (Larouche et al., 2019). However, the usage of large quantities of water in field-intensive production, i.e., approximately 300 L per tonne of larvae, makes this technique environmentally harmful. Surprisingly, slow slaughtering methods such as freezing

did not prevent protein and lipid degradation (Caligiani et al., 2019; Leni et al., 2019). Furthermore, Nyangena et al. (2020) have shown that various processing techniques, i.e., toasting, boiling, solar, and oven drying, can affect the chemical composition of insects. It should be highlighted that most authors observe an adverse effect of CP dilution during the boiling water process (Egan et al., 2014; Manditsera et al., 2019). It is well known that temperature can disrupt the quality of protein and further its availability (Ibáñez et al., 2020). Thus, subsequent performance results of farm animals fed insect-based diets can be negatively affected by a reduction in the digestibility coefficients of crude protein and amino acid availability. The protein dispersibility index (PDI) of *H. illucens* larvae meals varied significantly and was characterized in the range from approximately 19% to 60% (Table 2). Low PDI values indicate the occurrence of the Maillard reaction and binding of lysine to carbohydrates, which makes indigestible complexes. Additionally, temperature treatment may result in the oxidation, aggregation, and formation of Schiff bases (Bax et al., 2012). This result is in line with Huang et al. (2019), where conventionally dried (60 °C in a drying oven to constant weight) *H. illucens* larvae were characterized by a better digestible indispensable amino acid score and digestibility than the microwave (500 W for 15 min) method, which may polymerize the protein and impede its digestion. It was confirmed for *T. molitor* and *A. domesticus* that oven drying (150 °C

Table 2
Comparison of the protein dispersibility index (PDI) values of the selected feed materials.

Item	Process	Parameters	PDI, %	Reference
Feed material				
Whole soybeans	–	–	88.6	Bruce et al. (2006)
Soybeans	Roasted	143 °C	18.6	
Raw maize-based food	–	–	69.3	Lasekan et al. (1996)
Maize-based food	Extrusion	100 °C	46.6	
Maize-based food	Extrusion	120 °C	29.6	
Maize-based food	Extrusion	135 °C	18.9	
Animal byproducts	Raw	–	7.87 to 8.28	Pérez-Calvo et al. (2010)
Animal byproducts	Rendered	141.8 °C, 23.8 min; 2.3 bars	11.02 to 15.42	
<i>Hermetia illucens</i> larvae defatted meal	Drying	100 °C, 24 h	22.60	Authors data (unpublished)
<i>H. illucens</i> larvae full-fat meal	Drying	100 °C, 24 h	19.38	
<i>H. illucens</i>	Drying	70 °C, 48 h	29.05	Ravi et al. (2020)
<i>H. illucens</i>	Freezing	–80 °C, 24 h freeze-dried	52.86	
<i>H. illucens</i>	Microwave drying	450 W, 20 min	31.15	
<i>H. illucens</i>	Scalding	Boiling water 5 min; freezing at –18 °C and freeze-dried	34.35	
<i>H. illucens</i>	Blanching	Steam 5 min; freezing at –18 °C and freeze-dried	33.70	
<i>H. illucens</i>	Microwave drying	900 W at 120 °C, 5 bars pressure 5 min; frozen –18 °C and freeze-dried	42.45	
<i>H. illucens</i>	Fat extraction	n-hexane	29.09	Ravi et al. (2019)
<i>H. illucens</i>	Fat extraction	2-methylxolane	31.55	
Average PDI value of soybean by origin				
Argentina		10.3 to 23.9		Ibáñez et al. (2020)
Brasil		8.9 to 17.6		
USA		8.8 to 45.7		
India		9.6 to 33.6		

1 bar = 100 kPa.

for 30 min and 200 °C for 10 min) and autoclaving significantly decreased in vitro CP disappearance during enzymatic hydrolysis (Poelaert et al., 2016). Finally, the storage of insect-derived products can also negatively affect their nutritive value. Independent of the packages, i.e., made of plastic, polyethylene, or polypropylene, the ambient or refrigerated storage temperature conditions significantly reduced house cricket meal mono- and polyunsaturated fatty acids in the period from 45 to 90 d (Kamau et al., 2017).

The diverse microbiota of the insects' gastrointestinal tract (GIT) (Daniele et al., 2022; Zhineng et al., 2021) may play an important role in the contamination of the final products. Because insects are processed with the gastrointestinal tract, evisceration is not possible. Therefore, all of the abovementioned technological issues should also relate to microbiological safety and quality. In conclusion, the development of optimal processing techniques is the key to ensuring that the nutritional value of feed materials made from insects is not destroyed; moreover, a balance between microbiological safety and biological value of the nutrients is important. It is therefore advisable to continue work on identifying effective methods of slaughter, drying, and storage.

4. Insects in petfood

The possible implementation of insect-derived products, mainly protein meals, in companion animals' nutrition allows to expand the branch of hypoallergenic diets (Böhm et al., 2017, 2018). The constantly increased availability of invertebrate biomass on the market has resulted in an enlarged number of commercial foods. It should be highlighted that the ancestors of domestic dogs and cats ingest invertebrates as a part of their natural diets (Behrendorff et al., 2016; Tiralla et al., 2021; Woolley et al., 2020). Thus, the implementation of “novel” insect ingredients is in fact back to nature. Moreover, in the case of the petfood industry where “fresh meat” application is becoming more important, the question of whether insect biomass should be implemented as a direct

replacement of vertebrate meat and its byproducts arises. In this case, drying and/or fat separation is avoided; however, appropriate devitalization of the larvae and further product stability are still important considerations.

4.1. Insect meals in petfood

The usage of various species, mainly *T. molitor*, as well as *H. illucens* larvae as the main source of protein in the diets of pets has not only a nutritional effect but also a beneficial environmental impact. It should be emphasized that the production of commercial pet food generates up to 30% of the environmental impact (including the use of land, water, fossil fuel, phosphate, and biocides) from animal production and emits 64 million tonnes of CO₂-equivalent methane and N₂O (Okin, 2017). This is caused by the significant amounts of pets kept in households, i.e., 703.3 million globally (Hughes and Macdonald, 2013). Additionally, the global warming potential (GWP) of insects, particularly *T. molitor* and *H. illucens*, is smaller, from four to twenty-eight times, than chicken, pork, and beef protein production (Beynen, 2020). Thus, the CO₂ equivalent per kg of product is stated at the level of 12 to 13 GWP/kg protein for insects, contrary to 50 or 335 GWP/kg of protein for chickens or beef production, respectively. Consequently, the provision of insect biomass into pet foods positively affects not only the diversification of hypoallergenic products but also stays in line with the idea of HORIZON2020, including the European Green Deal (ec.europa.eu). In addition to the abovementioned information, the most important from a practical point of view seems to be the palatability of insect biomass. Kierończyk et al. (2018b) showed that insects may be used in dog diets as an additional attractant; however, differences between sexes were observed. Accordingly, females preferred more *Shelfordella lateralis*, while males favored *T. molitor* larvae. Based on Beynen (2020), the distinction between dogs and cats is also noted. *H. illucens* larvae meal was more suitable for dogs when the cats preferred the *T. molitor* larvae product.

Nonetheless, in the case of cat acceptance, *H. illucens* meal was also tolerated by most animal use in the Paßlack and Zentek (2018) study. Importantly, the high inclusion level of *G. sigillatus* meal, i.e., up to 24% (Kilburn et al., 2020), as well as 20% of *H. illucens* larvae meal (Freel et al., 2021) did not trigger feed intake in dogs. Additionally, the total replacement of chicken fat used as an energy source in beagle dog diets by *H. illucens* larvae fat (5% inclusion) did not influence palatability.

The in vitro DM digestibility measurements indicate no obstacles to the use of *H. illucens*, *M. domestica*, and *T. molitor* larvae meals in dog nutrition, which are characterized by 81.4%, 88.6%, and 92.3%, respectively (Bosch et al., 2016). Furthermore, the essential amino acid availability was above 91%. The results of in vivo studies confirmed the possibility of insect meal usage in pet nutrition. Lisenko et al. (2018) suggested the possibility of *Nauphoeta cinerea*, *Gromphadorhina portentosa*, and *Zophobas morio* larvae meal usage in beagle diets up to 15% without a negative effect on nutrient digestibility, fecal metabolites, or the excreta microbiota. Furthermore, Russo et al. (2019) concluded that DM digestibility was higher in the *H. illucens* meal diet than in the control feed with deer byproducts used as a main source of protein. Additionally, Freel et al. (2021) indicated that the administration of up to 20% *H. illucens* meal, as well as the partial (50%) or total replacement of chicken fat by *H. illucens* larvae fat in the Beagle dog diet, resulted in no adverse effect on nutrient and energy availability.

4.2. Insect functional properties in petfood

However, in the available literature, there are scarce data in terms of experimentation carried out on dogs or cats to evaluate the potential effect of insect-based diets on pet organisms. The application of maggots at the level of 5% also did not influence dog growth, feed intake, blood hematology, biochemistry, or immune traits or reduce oxidative stress (Hong et al., 2020). Interestingly, the addition of a relatively small amount of *H. illucens* larvae meals, i.e., 1% or 2%, linearly improved the apparent total tract digestibility of DM (72% vs. 75%) and CP (73% vs 78.5%) and had a favorable impact on immune (tumor necrosis factor- α [TNF- α]) and anti-oxidative status (glutathione peroxidase) (Lei et al., 2019). Surprisingly, after 24% *Gryllobates siggylatus* was added to the beagle dogs' diets, the alpha and beta microbial diversity was not affected, while only a few genera/families, i.e., *Catenibacterium*, Lachnospiraceae, *Faecalitalea*, *Bacteroides*, *Faecalibacterium*, and Lachnospiraceae, were influenced; however, their abundance comprised less or near 1% of the total microbial community (Jarett et al., 2019). However, *G. siggylatus* meals at each inclusion level, i.e., 8%, 16%, and 24%, negatively affected the nutrient digestibility of crude protein, ether extract, and gross energy and increased the daily fecal output (Kilburn et al., 2020). This could be a result of low acidic chitinase gene expression in dogs and a consequence of decreased chitin digestibility, which is the lowest in comparison to mouse, chicken, pig, and bovine, even if the insect products are well tolerated (intake) by the animal (Tabata et al., 2018). However, some doubts still occur in the scope of disease transmission or heavy metal accumulation (Ibitoye et al., 2019). Due to the limitations of available studies, there is a need to significantly expand knowledge in terms of various insect species or chitin incorporation into pet diets and evaluation of their effects on the nutrient digestibility coefficients (in vivo), physiological and immunological response, and the GIT microecosystem, particularly during long-term studies.

Currently, the pet food market frequently offers diets based on the insect as a sole protein source. This process excludes the most allergenic products from the dogs' food, such as soy or chicken meat. There are limited data about the hypoallergenic properties of insects in terms of their inclusion in companion animal diets.

According to Lee et al. (2021), the defatted *T. molitor* meal-based diet offered to dogs for 12 weeks has the potential to diminish cutaneous lesions and skin barrier dysfunction. Furthermore, a positive effect on the improvement of lesion scores and coat quality in atopic dermatitis dogs was observed after 2 weeks of insect-based diet administration (Böhm et al., 2018). However, it should be emphasized that each protein above 20 kDa may cause an allergy (Lee et al., 2021). Furthermore, the history of food allergy shows that protein availability is a significant factor in its occurrence, i.e., the geographical access to specific ingredients and frequency of protein ingested (Prélaud, 1999). Thus, there is still a possibility of invertebrate-origin allergies appearing in the future. Nevertheless, there is a priority to improve our knowledge about the effect of tropomyosin, arginine kinase, and other allergens present in insect biomass on companion animal health.

Eventually, dog owners have a positive attitude in terms of the future usage of insect products as an alternative to meat in dog food, particularly due to the benefits of reducing environmental pressure, and additionally claim that invertebrate biomass is nutrition's sufficient substitute or replacement for current products (Ibitoye et al., 2019).

5. Insects in poultry nutrition

5.1. Insect meals as a functional feed additive for poultry

According to the abovementioned challenges in terms of insect biomass production limitations, the current application of insect meals should be considered a potential functional feed additive according to their health-promoting properties (Gasco et al., 2018). It is well documented that chitin, as well as antimicrobial peptides (AMPs), occurring in invertebrates can positively affect the growth performance, GIT microbiota, and immune response of birds (Gasco et al., 2020; Józefiak and Engberg, 2017). It is indicated that feeding broiler chickens with meals as a source of chitin resulted in a decrease in the intestinal population of bacteria such as *Escherichia coli* and *Salmonella*; in contrast, the effect has not been confirmed in birds fed purified chitin. Insects have also been investigated as promising sources of antimicrobial peptides. According to the Antimicrobial Database (aps.unmc.edu), to date, 326 AMPs have been identified from insects. Research performed in vitro investigating the antimicrobial activities of fractionated extracts and AMPs purified from insects identified 16 peptides in samples of *H. illucens* and 16 in *T. molitor* (Tables 3 and 4). The inhibition activities of peptides extracted from *H. illucens* have been proven against gram-negative bacteria, *E. coli*, *E. coli* serotype O157:H7, *Salmonella pullorum*, *S. typhimurium*, *S. enteritidis*, *Enterobacter aerogenes*, and *Pseudomonas aeruginosa*; gram-positive bacteria, *Staphylococcus aureus*, methicillin-resistant *S. aureus* (MRSA), *S. epidermidis*, *Streptococcus suis*, *Listeria ivanovii*, *Bacillus subtilis*, and *Micrococcus luteus*; and fungi, *Rhizoctonia solani*, *Sclerotinia sclerotiorum*, and *Candida albicans* (Table 3). To investigate the pharmacological activities of novel antibacterial peptides extracted from *T. molitor* against gram-positive bacteria, such as *B. subtilis*, *S. aureus*, *S. epidermidis*, *S. pyrogenes*, *M. luteus*, and *Corynebacterium diphtheriae*, as well as gram-negative bacteria, such as *E. coli*, *Shigella flexneri*, *P. aeruginosa*, and *Proteus vulgaris*, and yeasts, such as *S. cerevisiae* and *C. albicans*. Research performed in vivo indicated the beneficial effects of synthetic AMP-A3 and AMP-P5 on the growth parameters of broiler chickens (Choi et al., 2013a, 2013b; Wang et al., 2016). Moreover, the addition of synthetic cecropins to broiler diets decreased pathogenic bacteria and enhanced intestinal villus height in the duodenum (Wen and He, 2012). Therefore, it is suggested that cecropin can be a possible alternative to some antibiotics used in poultry production.

Table 3
Antimicrobial peptides (AMPs) from *Hermetia illucens* inhibited microorganisms.

AMP name	Source/samples	Amino acid sequence	Techniques	Inhibited microorganisms	MIC	AMP gene expression	Ref.
Cecropin-like peptide 1 (CLP1)	Hemolymph of immunized <i>H. illucens</i> larvae <i>S. aureus</i> (KCCM 40881, KCCM 12256)	MNFTKLFVVFA VVLVAFAGQSEAGWRK RVFKPVEKFGQVRDAGVQ GIAIAQQGANVLATARGGPPQQG	Fast protein liquid chromatography (FLPC), high-performance liquid chromatography (HPLC), matrix-assisted laser desorption/ionization-time-of-flight (MALDI-TOF) mass spectrometry (MS), RT-PCR	<i>Escherichia coli</i> KCCM 11234 <i>Enterobacter aerogenes</i> KCCM 12177 <i>Pseudomonas aeruginosa</i> KCCM 11328 MRSA KCCM 40881 <i>Staphylococcus aureus</i> KCCM 12256 <i>S. epidermidis</i>	0.52 to 1.03 µmol/L 1.03 to 2.07 µmol/L 1.03 to 2.07 µmol/L ND ND ND	AMP gene expression was increased in the muscle and trachea.	Sultana et al. (2021), Park and Yoe (2017a)
Cecropin-like peptide 2 (CLP2)	Hemolymph of immunized <i>H. illucens</i> larvae	MNFAKLFVFAIVLVAFSGQ SEAGWVKRVFKPVEKLGQR VRDAGIQGLEIAQQGANVLATA RGGPPQQG	FLPC, HPLC, MALDI-TOF, MS, RT-PCR	<i>E. coli</i> MRSA	–	–	Park and Yoe (2017a)
Cecropin-like peptide 3 (CLP3)		MNFTKLFVFAVVLIAFSGQSEA GWWKRVFKPVERLGQVRDAG IQGLEIAQQGANVLATVRGGPPQQG GWLKKGKMKFILGTLTIAVIAIFGQC		<i>Enterobacter aerogenes</i> <i>P. aeruginosa</i>			
CecropinZ1	Crushed <i>H. illucens</i> larvae immunized with <i>S. aureus</i> and <i>E. coli</i>	QAATWSYNPNNGGATVWTANVAATAR	3D structures of the AMP genes; protein expression, antimicrobial activity assay	<i>E. coli</i> <i>S. aureus</i> <i>Rhizoctonia solani</i> <i>Sclerotinia sclerotiorum</i>	15 to 30 µg/mL 54 µg/mL 98 µg/mL	–	Elhag et al. (2017)
Cecropin 1 (Hicec1)	Hemolymph of <i>H. illucens</i> larvae immunized <i>Lactobacillus</i> species	Full sequence not presented in references	Antimicrobial activities; analysis of AMPs transcripts	<i>S. aureus</i> KCCM 40881, <i>E. coli</i> KCCM 11234, <i>Salmonella pullorum</i> KVCC-BA0702509, <i>Salmonella typhimurium</i> KCCM 40406, <i>Salmonella enteritidis</i> KCCM 12021	Range 100 to 200 µg/ 100 µL for all analyzed microorganism	–	Lee et al. (2020)
Defensin-like peptid 1 (DLP1)	Hemolymph of immunized <i>H. illucens</i> larvae	MRSVLVGLIIVAAFAVYTSAPQ YQLQYEEDGLDQAVELPIEEEQ LPSQVVEQHYRAKRATCDLLSPF KVGHAACALHICALGRRGGWCD GRAVCNCR	HPLC, concentration assessment kit BCA (Pierce)	–	–	–	Xia et al. (2021)
Defensin-like peptid 2 (DLP2)	Hemolymph of immunized <i>H. illucens</i> larvae with MRSA (ATCC43300)	MRSILVGLIIVAAFAVYTSAPQYQLQYE EDGPGYALELPSEEEGLPSQVVEQHYRAKRA TCDLLSPFKVGHAAACALHICIAMGRGGWCD GRAVCNCR	HPLC, antimicrobial ability	<i>S. aureus</i> ATCC25923 <i>S. aureus</i> ATCC43300 <i>S. aureus</i> ATCC6538 <i>S. aureus</i> CICC546 <i>Streptococcus suis</i> CVCC606 <i>Listeria ivanovii</i> ATCC19119 <i>E. coli</i> CVCC1515 <i>E. coli</i> CICC21530 serotype O157:H7 <i>Salmonella typhimurium</i> ATCC14028 <i>S. enteritidis</i> CMCC50336	0.1 µmol/L 0.12 µmol/L 0.23 µmol/L 0.93 µmol/L 0.12 µmol/L >29.97 µmol/L	–	Xia et al. (2021) Li et al. (2017)
Defensin-like peptid 3 (DLP3)	Hemolymph of immunized <i>H. illucens</i> larvae	MRSILVGLIIVAVFGVYTSAPQYQLQYEED GPEYALVPIEEEEELPSQVVEQHYRAKRATCD LLSPFGVGHAAACAVHCIAMGR GGWCDRAVCNCR	FLPC, HPLC, MALDI-TOF, MS, RT-PCR	<i>E. coli</i> , MRSA	–	–	Li et al. (2017) Xia et al. (2021) Park and Yoe (2017b)
Defensin-like peptid 4 (DLP4)	Hemolymph of <i>H. illucens</i> larvae immunized with <i>S. aureus</i> KCCM 40881, and MRSA ATCC43300	MVHCQPQFLETEGDQQLPEVVAEVDD VVDLVAIPEHT REKRATCDLLSPFKVGH AACAHAICARGKRGGWCDKRAVCNCRK	FLPC, HPLC, MALDI-TOF, MS, RT-PCR	MRSA clinical isolated, multidrug resistant <i>S. aureus</i> KCCM 40881 <i>S. aureus</i> KCCM 12256 <i>Bacillus subtilis</i> KCCM 11316 <i>Staphylococcus epidermidis</i> KCCM 35494 not observed antimicrobial activity against Gram-negative bacteria <i>E. coli</i> KCCM 11234, <i>Enterobacter aerogenes</i> KCCM 12177, <i>P. aeruginosa</i> KCCM 11328 <i>S. aureus</i> KCCM 40881	0.5 to 1.17 µmol/L 0.06 to 1.17 µmol/L 1.17 to 2.34 µmol/L 0.02 to 0.04 µmol/L 0.59 to 1.17 µmol/L –	<i>DLP4</i> gene expression increased in fat body, muscle, and trachea	Xia et al. (2021) Li et al. (2017) Park et al. (2014)

Defensin 1 (hidef1)	Hemolymph of <i>H. illucens</i> larvae immunized <i>Lactobacillus</i> species	Sequence available in Antimicrobial Peptides Database (AP03308): ATCDLLSAT KVKSTACAAH CLLKGHHGGYCNKSLVVCVR MASKFLGNPNHNIGGGVFAA GNTRSNTPSLGAFTLNLDHSL GVSHITTPGVSDTFQNRRLNLL KTPDHRVDANVFNSTRNLNNGF AFDKRGGSLDYTHRAGHGLSLGA SHIPKFGTTAELTGKANLWRSPPG LSTFDLTGSASRTFGGPMAGRNNF GAGLGFSHRF	Antimicrobial activities, analysis of AMPs transcription	<i>E. coli</i> KCCM 11234 <i>Salmonella pullorum</i> KVCC-BA0702509 <i>S. typhimurium</i> KCCM 40406 <i>S. enteritidis</i> KCCM 12021	Range 100 to 200 µg/100 µL for all analyzed microorganism	—	Lee et al. (2020)
<i>H. illucens</i> attacin (HI-attacin)	Immunized <i>H. illucens</i> larvae with <i>E. coli</i> ; fat body, muscle, fore-gut, mid-gut, hind-gut, Malpighian tubule, and trachea samples	—	—	<i>E. coli</i> KCCM 11234 <i>S. aureus</i> KCCM 40881 MRSA	—	HI-attacin transcripts levels a 27.5-fold increase in the fat body, a 4-fold increase in fore-gut, a 10.2-fold increase in muscle, and a 3.7-fold increase in the trachea comparing to control	Shin and Park (2019)
Sarcotoxin 1, 2a, 2b, and 3	Crushed <i>H. illucens</i> larvae immunized with <i>S. aureus</i> , and <i>E. coli</i>	Sarcotoxin 1: GWLKRKIGMKFIL GTTLAIVVAIFGQCQAATWSYNPN GGATVVTANVAATAR Sarcotoxin 2a: GWLKRKIGKKFILGTTLAIVVA IFGQCQAATWSYNPNGGATVVTANVAATAR Sarcotoxin 2b: GWLKR KIGKKFILGTTLAIVVAIFGQCQAAT WSYNPNGGATVVTANVAATAR Sarcotoxin 3: GWLKRKIGMMMK NSNFNSTEEREAAKKNYKRKYVP WFSGANVAATAR	Analysis of gene and 3D structures	<i>S. aureus</i> , and <i>E. coli</i> ; Four isoforms were detected for sarcotoxin: sarcotoxin 1, sarcotoxin (2a), sarcotoxin (2b), and sarcotoxin 3	—	—	Elhag et al. (2017)
StomoxynZH1	Crushed <i>H. illucens</i> larvae immunized with <i>S. aureus</i> , and <i>E. coli</i>	RGFRKHFNLPICVEGLAGD IGSILLGVG	3D structures of the AMP genes; protein expression, antimicrobial activity assay	<i>E. coli</i> <i>S. aureus</i> <i>Rhizoctonia solani</i> <i>Sclerotinia sclerotiorum</i>	15 to 30 µg/mL 27 to 54 µg/mL >98 µg/mL	—	Sultana et al. (2021) Elhag et al. (2017) Huang et al. (2020) Park et al. (2014)
Fractioned extract of <i>H. illucens</i> larvae	Lyophilized <i>H. illucens</i> larvae immunized with <i>S. aureus</i>	—	The water-soluble extract was applied to Sep-Pak C18, elution with 80% acetonitrile (ACN)	MRSA <i>Candida albicans</i> <i>Kocuria rhizophila</i> <i>Micrococcus luteus</i> <i>E. aerogenes</i> <i>B. subtilis</i> <i>E. coli</i> <i>P. aeruginosa</i> <i>S. epidermidis</i>	25 mg/mL 12.5 mg/mL 50 mg/mL	—	

AMP = antimicrobial peptide; MIC = minimal inhibitory concentration; MRSA = methicillin-resistant *Staphylococcus aureus*.

Table 4
Antimicrobial peptides (AMPs) from *Tenebrio molitor* inhibited microorganisms.

AMP name	Source/samples	Amino acid sequence	Techniques	Inhibited microorganisms	MIC	AMP gene expression	Ref.
Tenecin 1 (homolog of sapecin)	Hemolymph immunized larvae of <i>T. molitor</i> with <i>E. coli</i> ATCC K12, <i>S. aureus</i> ATCC RN4220; hemolymph of immunized larvae <i>T. molitor</i> with β -1,3-glucan	Sequence available in Antimicrobial Peptides Database (AP00354): VTCDILSVEAKGVKLNDAACAHAHLFRGRSGGYCN GKRVCVCRSGGYCNGKRVCCVCR	Reversed-phase (C18) open column chromatography, reversed-phase high-performance liquid chromatography (HPLC), tenecin-1 gene expression analysis	<i>Bacillus subtilis</i> ATCC 1768	2.0	–	Moon et al. (1994) Keshavarz et al. (2019) Roh et al. (2009)
				<i>B. subtilis</i> ATCC 6633	1.0		
				<i>S. pyrogenus</i> 77A	–		
				<i>S. aureus</i> SG 501	0.8		
				<i>M. luteus</i> ATCC 1024	5.0		
				<i>S. aureus</i> ATCC 6538	3.7		
				<i>S. pyrogenus</i> 308A	1.6		
				<i>S. epidermidis</i> ATCC 12228	8.0		
				<i>Micrococcus luteus</i> ATCC 9341	–		
				<i>Corynebacterium diphtheriae</i> ATCC 8024	–		
<i>C. diphtheriae</i> ATCC 8032	6.0						
<i>E. coli</i> ATCC 2592	>30						
<i>Shigella flexneri</i> ATCC 203	–						
<i>P. aeruginosa</i> ATCC 9027	–						
<i>Proteus vulgaris</i> OX-19 ATCC 6380	–						
Antimicrobial activities against <i>E. coli</i> and <i>Saccharomyces cerevisiae</i>	–	–	Roh et al. (2009) Keshavarz et al. (2019)				
Tenecin 2 (coleoptericin and diptericin-like peptide)	Hemolymph of immunized larvae of <i>T. molitor</i> with β -1,3-glucan	Full sequence not presented in references	Reversed-phase (C18) open column chromatography, HPLC, qRT-PCR and bactericidal activity analysis				
Tenecin 3	Immunized larvae of <i>T. molitor</i> with <i>E. coli</i> ATCC K12, <i>S. aureus</i> ATCC RN4220; construction of plasmids for producing MBP-tenecin 3 fusion proteins	GenBank: (AAA97579.1): DHHDGHLGGHQTGHQGGQQGGHLLGGHQQGGQPGGHLGGHQQGGIGGTGGQHGQHPGTGAGHQG GYKTHGH	Reversed-phase (C18) open column chromatography, HPLC; qRT-PCR; expression of MBP-tenecin 3 fusion protein in <i>E. coli</i> ; purification of MBP fusion proteins; index of cell growth of various fungi with treatment of MBP-tenecin 3	Antifungal activity <i>C. albicans</i> KCFC1940 did not inhibit the growth of <i>Aspergillus nidulans</i> FGSC4, <i>S. cerevisiae</i> DBY747, <i>E. coli</i> , and <i>S. aureus</i>	–	Abundant transcription of tenecin-3 RNA in larvae and adults, but little in pupae; present constitutive expression in the hemolymph.	Jung et al. (1995) Lee et al. (1996) Keshavarz et al. (2019) Lee et al. (1995)
Tenecin 4	Injection of polymeric diaminopimelic acid (DAP)-type peptidoglycan (PG); immunized larvae of <i>T. molitor</i> with <i>E. coli</i> ATCC K12, <i>S. aureus</i> ATCC RN4220	GenBank (BAL04117.1): MLKAVQFALSCTILSAAAPTASSETKWDIE DPGKLIKQHS GTIFNNG GHKLDGEAYGSKSLVDRRDPVAVFGGLKDYNNHSGSSLSVSAQHKHRGTRVGVGKYNLYRNGP FHADVSGKYDRITYGGASSNPSFSTHLTGTVD	The antibacterial activities of AMPs with radial diffusion assays; analysis of tenecin-4 gene expression (qRT-PCR)	<i>E. coli</i> ATCC K12 <i>S. aureus</i> Cowan 1 No bactericidal activity against <i>B. subtilis</i> ATCC 6633, and <i>C. albicans</i> TIMM 1768	0.5 5.0 –	Observed changes of AMP gene expression.	Chae et al. (2012) Keshavarz et al. (2019)
Attacin 1a	Immunized larvae of <i>T. molitor</i> with <i>E. coli</i> ATCC K12, <i>S. aureus</i> ATCC RN4220/eggs, young and late larvae, prepupae, pupae, and adults; the whole larvae, hemocytes, gut, Malpighian tubules, and fat body	GenBank (AXG21618.1): MQKQLIVSILAFASLAFATADNKIPPPKPEDGQRETKWVKVEDPG IINLQHREKLYESGPHRFDATAAYKKNFVDKMDPARTIARVDYKYLPGDTSGLVQAENQRFGT VLSAEATRNLKDKRKSLLDVGVNQGTFSFV RSEPPFGGFVRGRF	Analysis of AMP gene expression (qRT-PCR), and antimicrobial activity	<i>E. coli</i> ATCC K12, <i>S. aureus</i> ATCC RN4220, <i>C. albicans</i> ATCC	–	AMP gene expression observed in young larvae in fat body, hemocytes, and gut.	Keshavarz et al. (2019)
Attacin 1b		GenBank: AXG21619.1: MNMQTVYIILACC LASALARPGNTKPEDQSQTKWGVRDGVNLNVE HHGNLYKNDNHRFDGTASVTKNFVDNKDPLL VGGRVVYKHLPSNSAIGLAVNAGQFGTKVDLEA SRTLKDRFSQFDAGVSYGQRFQPGFNGSEPVFVGGFIRGRF			–		
Attacin 2		GenBank: AXG21617.1: MFKLIVLALVGLAAVSAYEVV QDDQGEFFLPLHRQRQTSVDISKSNPGRVATVSH QGTIFNNGDHRLDGGAFASKQFRPSGPATVGGKLG YSHVPSGSLNVGAQRTQRFQTDVTSATGANLWRRG NARLDVAVGQYNRHFGVGGTGRPNYYGGLQFSHRF			–		
Coleopterins 1	Immunized larvae of <i>T. molitor</i> with <i>E. coli</i> ATCC K12, <i>S. aureus</i> ATCC RN4220/the fat body, hemocytes, gut, and Malpighian tubule	Full sequences not presented in references	Analysis of coleopterins gene expression (qRT-PCR), and antimicrobial	<i>E. coli</i> ATCC K12, <i>S. aureus</i> ATCC RN4220; observed no effect on <i>C. albicans</i> AUMC 13529	–	AMP gene expression observed in gut, and Malpighian tubules.	Keshavarz et al. (2019)
Coleopterins 2					–	AMP gene expression observed in hemocytes, and gut; not observed in fat body of young larvae.	Keshavarz et al. (2019)

According to [Benzertiha et al. \(2020a\)](#), even a relatively small amount of *T. molitor* and *Z. morio* full-fat meals (2 or 3 kg per tonne of diet) supplemented on top can significantly improve the growth performance results, including body weight gain (BWG) and feed intake (FI), without a negative effect on the feed conversion ratio (FCR). This finding is in line with [Islam et al. \(2016\)](#), who reported improvement in BWG after 0.4% *T. molitor* or *Z. morio* addition to the broiler diet. Furthermore, 1% *T. molitor* full-fat meal supplementation positively affected the growth performance results ([Ballitoc and Sun, 2013](#)). No detrimental effect of relatively small amounts of insect inclusion on the apparent nutrient digestibility coefficients and pancreatic enzyme activities was noticed ([Benzertiha et al., 2019a](#)). The observed positive production effects are connected to beneficial microbial shifts, particularly in the ceca, where *Z. morio* meal (0.2% supplementation) enhanced the abundance of Actinobacteria, including the Bifidobacteriaceae family, and *Lactobacillus agilis* number, while *T. molitor* meal increased the Clostridia class level, especially Ruminococcaceae ([Józefiak et al., 2020](#)). Moreover, the inhibition activity against the *Bacteroides-Prevotella* cluster and *Clostridium perfringens* at this segment was noticed mainly after *T. molitor* (0.3%) and *Z. morio* (0.2%) addition. Bird GIT microbiota modulation, i.e., an increase in the number of butyrate-producing bacteria in the crop and *Lactobacillus* spp./*Eubacterium rectale* clusters in the ileum, was observed even when 0.05% *S. lateralis* was implemented ([Józefiak et al., 2018](#)). Moreover, due to

the wide spectrum of potential bird responses, i.e., in terms of productivity, and GIT microbiota modulations after insect biomass implementation in poultry diets, further investigation should be stressed on the administration of a relatively small amount of these products. In particular, [Benzertiha et al. \(2020b\)](#) suggested a positive effect on the decrease in the bursa of Fabricius relative weight, as well as immunoglobulin M concentration. Furthermore, the application of 0.3% *H. illucens* full-fat meals in young turkey diets resulted in more efficient anti-inflammatory, immune stimulatory, and antioxidant impacts than commonly used monensin ([Kozłowski et al., 2021](#)).

5.2. Insect fat as an energy source for poultry

Most of the research on the application of the insect in animal nutrition focuses on protein usage; however, fat is also an important nutrient present in insect biomass, sometimes in ranges comparable to CP ([Benzertiha et al., 2020b](#)). Moreover, fat derived from insects can fully replace environmentally unfriendly and commonly used feed materials such as palm or soybean oils used in poultry nutrition ([Table 5](#)). It should be emphasized that the quantity of crude fat as the second main nutrient in the invertebrate body varies from 1.3% (as is) for *Carebara* sp. to 61.1% (in DM) for termites ([Bessa et al., 2020](#); [Bukkens, 1997](#)) and is highly dependent on the rearing substrate ([Kierończyk et al., 2020](#)). To

Table 5
Effect of various invertebrate fats used as an energy source carrier on the selected poultry species organism response.

Fat source	Species	Replaced oil	Inclusion level	Result	Reference
<i>Hermetia illucens</i>	Broiler chickens	Soybean oil	50%; 100%	The fatty acid profile was adversely affected.	Schiaivone et al. (2016)
<i>H. illucens</i>	Broiler chickens	Soybean oil	50%; 100%	No detrimental effects.	Schiaivone et al. (2018)
<i>H. illucens</i>	Broiler chickens	Soybean oil	25%; 50%; 75%; 100%	The positive impact on FCR in the first 2 weeks of age. Beneficial reduction of jejunum and ileum weight.	Kierończyk et al. (2020)
<i>H. illucens</i>	Broiler chickens	Soybean oil	50%; 100%	Partial replacement induced elongation of the villi. The effect on lipase activity limitation. Acetate was reduced and butyrate enhanced in both <i>H. illucens</i> fat inclusions.	B. Kim et al. (2020a)
<i>H. illucens</i>	Broiler chickens	Soybean oil	50%; 100%	Reduction of the gizzard relative mass. Increasing of saturated, monounsaturated fatty acids, and limitation of polyunsaturated fatty acids, and the unsaturated and saturated fatty acids ratio.	B. Kim et al. (2020b)
<i>H. illucens</i>	Broiler chickens	Soybean oil	50%; 100%	The fatty acid profile was negatively enriched in saturated fatty acids.	Cullere et al. (2019)
<i>H. illucens</i>	Broiler chickens	Soybean oil	50%; 100%	The negative microbiota shift in the birds' crop resulted from deficient releasing of lauric acid; the beneficial impact on the hindgut microecosystem.	Kierończyk et al. (2021)
<i>H. illucens</i>	Broiler chickens	Corn oil, coconut oil	100%	Decreasing of feed conversion ratio (1 to 30 d) contrary to corn oil. Limitation of cholesterol and high-density lipoproteins (HDL) in the serum. Increasing the breast meat yellowness and enrich the abdominal fat in medium-chain fatty acid.	Y.B. Kim et al. (2020)
<i>H. illucens</i>	Turkeys	Soybean oil	50%; 100%	The limitation of trypsin activity, and immune status trait concentrations (interleukin-6, tumor necrosis factor- α); the reduction of the crop digesta pH, and inhibition of Enterobacteriaceae populations in the jejunal content. Increase of total cholesterol, HDL and low-density lipoproteins (LDL) concentration in the plasma.	Sypniewski et al. (2020)
<i>H. illucens</i>	Laying hens	Soybean oil	100%	No effect on the growth and laying performance, egg weight, and quality.	Heuel et al. (2021)
<i>Tenebrio molitor</i>	Broiler chickens	Palm oil, poultry fat	100%	The positive impact on the limitation of fat, triglycerides, and total cholesterol in the liver. Improvement of fatty acid profile in the liver and breast meat.	Benzertiha et al. (2019b)
<i>T. molitor</i>	Broiler chickens	Soybean oil	100%	The growth performance parameters improvement till 21 d of age and digestibility through the entire rearing period or exhibit a similar effect to soybean oil. The beneficial effect on the meat quality was noticed.	Kierończyk et al. (2018a)
<i>Zophobas morio</i>				<i>Z. morio</i> fat generally performed comparably to soybean oil.	

date, only three insect species have been considered an alternative energy source in poultry diets, i.e., *T. molitor*, *Z. morio*, and *H. illucens*. Nevertheless, significantly more insects, particularly Hymenoptera, Coleoptera, Lepidoptera, Homoptera, Hemiptera, and Orthoptera orders, are evaluated in human nutrition as an energy source (Ramos-Elorduy, 2008).

In general, no detrimental effect of the partial or total inclusion of insect fat on the growth performance and productivity parameters was observed. These results suggest that the metabolizable energy values of insect fat for broilers (Kierończyk et al., 2018a), laying hens (Heuel et al., 2021), and turkeys (Sypniewski et al., 2020) are comparable to soybean oil. Nevertheless, the most important challenge in the case of insect fat provision to poultry diets seems to be the fatty acids profile of the final products, i.e., breast and leg meat, which are highly dependent on the quality of the feed material. Thus, there is a need to improve not only the quantity of the dietary fat of insect biomass through the diet composition and technique of extraction but also its quality, particularly in terms of economically justified species such as *H. illucens*. In the available literature, the authors mainly focus on the lauric acid (C12:0) concentration to enhance the functional properties of the *H. illucens* larvae fat (Borrelli et al., 2021; Dabbou et al., 2020; Sypniewski et al., 2020). However, the results of these studies indicate a need to improve the fatty acid composition of the *H. illucens* larvae fat by increasing the *n*-3 level and the polyunsaturated fatty acids (PUFAs) concentration which may result in enhanced broiler meat quality preferred by the consumer. To date, the most suitable and beneficial product from the final product's quality point of view is *T. molitor* larvae fat inclusion in broiler diets. Mealworm fat improves the fatty acids profile by lowering the level of saturated fatty acids (SFAs) and increasing unsaturated fatty acids (UFAs) in comparison to soybean oil. Furthermore, the meat from broilers fed *T. molitor* fat characterizes atherogenic and thrombogenic indexes similar to soybean oil (Kierończyk et al., 2018a).

Eventually, in addition to the growth performance results and the possibility of applying insect fat in poultry nutrition, the consumer palatability of the final products should be evaluated as a crucial factor determining the economic success of this sustainable and novel feed material. To date, only a few scientific reports have been published; however, none of those have emphasized the adverse effect on consumer preferences. Additionally, it should be highlighted that there is a shortage of data about the poultry product preference test. Broiler chickens' meat sensory traits were not affected by even the total replacement of soybean oil by *H. illucens* larvae fat (Cullere et al., 2019). Additionally, partial (50%) or total inclusion of *T. molitor*, as well as *H. illucens* as an energy source in rabbit diets, exhibit similar consumer acceptance in terms of meat palatability as in the control group (soybean oil) (Gasco et al., 2019). No changes in overall food liking or experience of selected bakery products, which include up to 50% butter derived from *H. illucens* larvae fat, were noted (Delicato et al., 2020). Thus, it could be concluded that there is no risk of insect fat administration as an energy source in poultry diets from bird production, as well as the consumer point of view; however, a continuation of UFA enrichment evaluation is needed to improve the quality of the final product.

5.3. Functional properties of insect fat in poultry nutrition

Furthermore, the intestinal microbiota composition is not adversely affected by insect fat inclusion, particularly in terms of *H. illucens* larvae fat, which is characterized by the highest medium-chain fatty acid (MCFA) content with the dominant lauric acid (C12:0) concentration, in contrast to other invertebrate species.

Lauric acid exhibits significant inhibitory activity against gram-positive and gram-negative bacteria, including bird or poultry product pathobiota such as *Pasteurella multocida*, *Yersinia enterocolitica*, and *Listeria monocytogenes* (Dabbou et al., 2020). Furthermore, the results of Zeitz et al. (2015) underline the positive effect of lauric acid against Enterobacteriaceae, *Campylobacter jejuni*, and *E. coli*. Finally, lauric acid, characterized by strong inhibitory activity in the case of *C. perfringens* (Timbermont et al., 2010), which is an etiologic factor of necrotic enteritis, causes 6 billion USD costs in poultry flocks worldwide (profit lost per bird is estimated at US\$ 0.062) (Wade and Keyburn, 2015). Thus, there are premises to define *H. illucens* larvae fat as a functional feed material. The antiviral and antiparasitic modes of action were also observed. Nevertheless, a negative microbiota population shift in the bird crop was noted, which is explained as insufficient lauric acid release at this segment (Kierończyk et al., 2021).

6. Insects in swine nutrition

Although boar (*Sus scrofa*) in wild conditions mainly ingest plant-origin material, invertebrates, particularly the wide spectrum of insect species in various stages of development, are constantly present in their diets. The most frequently consumed insects are in the following orders: Anoplura, Coleoptera, Diptera, Hymenoptera, Lepidoptera, Orthoptera, and Trichoptera (Herrero et al., 2006). They play the main role as compensation for protein deficiencies when the source of this nutrient is scarce (Schley and Roper, 2003). Additionally, insects, as a rich source of iron (Fe), may be an important basis of this microelement supplementation in wild piglet diets. Furthermore, Tabata et al. (2018) showed that pigs are well adapted to take material rich in chitin via the high activity of acidic chitinase (Chia mRNA) gene expression. Kawasaki et al. (2021) noticed that even 14-day-old piglets can synthesize chitin-degradable enzymes, and acidic mammalian chitinase gene expression rises in the whole stomach weight parallel to the animal's age. Thus, it is not surprising that in the available literature, the usage of insect-derived feed materials is efficiently implemented at each pig rearing phase, i.e., nursing (Driemeyer, 2016), weaning piglets (Spranghers et al., 2018), growing (Chia et al., 2019), and finishing pigs (Yu et al., 2019a). In general, no detrimental effects in terms of growth performance results were noticed during *H. illucens* larvae meal or dietary fat, as well as *T. molitor* larvae meal, as the most commonly used protein and energy source in swine nutrition, i.e., fishmeal, soybean meal, corn and soybean oils (Ao and Kim, 2019; Biasato et al., 2019; Heugten et al., 2019; Ko et al., 2020; Meyer et al., 2020).

6.1. Insect meals in pig nutrition

It should be emphasized that in the experimental conditions, the insects' meals were administered up to 18.5% or 19.06% (Chia et al., 2019; Håkenåsen et al., 2020), while usually up to 10% inclusion is used (Biasato et al., 2019; Dankwa et al., 2000; Meyer et al., 2020). Due to the high nutritive value variability between insects, the obtained results between authors differ; however, some improvement effects on the BWG, FI, and FCR were observed (Jin et al., 2016; Yu et al., 2019a, 2020a). This result is in agreement with the linear increase in DM and CP digestibility coefficients, as well as N retention in weanling piglets fed 1%, 2%, or 4% *T. molitor* larvae meal (Jin et al., 2016). It should be highlighted that the digestible lysine in the *H. illucens* larvae meals (full-fat and defatted) is comparable to soybean meal, blood meal, and fishmeal (Crosbie et al., 2020). Some differences between full-fat and defatted meals in the scope of standardized ileal digestibility of arginine, valine, alanine, and proline were noticed, while N

retention, as well as N digestibility, was not affected. Furthermore, no influence in terms of fecal DM or the fecal score was observed in weaned piglets fed diets containing up to 19.06% *H. illucens* meal (Håkenåsen et al., 2020). Similarly, Yu et al. (2020a) did not show any changes in the diarrhea rate (from 4% to 7%) when full-fat *H. illucens* larvae meal was administered up to 4%. Even live *H. illucens* larvae administration did not affect the DM of piglet feces (Ipema et al., 2021). Additionally, no enhanced fecal gas emissions, i.e., ammonia, hydrogen sulfide, and total mercaptans, were noticed after *H. illucens* incorporation into weaned pig diets (Ao et al., 2020). It needs to be highlighted that *H. illucens* meal seems to be more suitable for piglets (25 kg), as well as growing pigs (60 kg), than *Spirulina platensis* meal in terms of N digestibility. Consequently, *H. illucens* meal can be considered more environmentally friendly than algae in the scope of N excretion limitations (Neumann et al., 2018). Jin et al. (2016) confirmed the linear improvement of digestibility of DM, CP, and the tendency in terms of crude ash during *T. molitor* larvae addition (1.5%, 3%, 4.5%, 6%) to weaning piglet diets. Simultaneously, nitrogen excretion was linearly reduced, while the control group (soybean meal) was characterized by the highest nitrogen footprint. Contrary to the abovementioned results, Yu et al. (2020a) showed that the 1%, 2%, and 4% inclusion of full-fat *H. illucens* meal negatively affects CP and crude fat digestibility in a dose-dependent manner. Additionally, Ao and Kim (2019) observed decreased digestibility coefficients of DM and nitrogen in weaning pigs fed *Ptectious tenebrifer*; however, the adverse effect was noted only during 50% replacement of fish meal. Similar to the results of Ao et al. (2020), only partial replacement of fishmeal was negatively affected by *T. molitor* larvae meal. Despite the above, the results of Altmann et al. (2019) suggest that the inclusion of *H. illucens* larvae meal improved the quality of pork meat by increasing PUFAs and reducing SFAs and monounsaturated fatty acids (MUFAs), and the overall odor and juiciness were improved. Simultaneously, no adverse effect on carcass yield was found. Additionally, Chia et al. (2021) highlighted that the usage of *H. illucens* meal as a total substituent of fishmeal significantly improved fasted and carcass weight, as well as increased fat content in loin muscle. Moreover, finishing pig tissues (heart, kidney, liver, lungs, loin muscle, and spleen) are characterized by increased macroelement concentrations, i.e., K and P, as well as microelements, i.e., Fe or Zn. Yu et al. (2019a) suggests that the inclusion of 4% or 8% *H. illucens* meal to finishing pig diets resulted in increased loin eye area, marbling scores, and inosine monophosphate concentration, while 4% addition increased intramuscular fat content in the longissimus dorsi muscle.

Even if it is only possible to add insect biomass to swine nutrition in relatively small amounts (up to 3%) under practical conditions, some advantages can be observed. It should be highlighted that the results of Choi et al. (2019) demonstrated that the 1%, 2%, and 3% inclusion of *H. illucens* meal used as a replacement of soybean meal in pigs' diets may constitute similar economic efficiency (feed cost per kilogram weight gain) and simultaneously improve the average daily gain and DM digestibility. Chia et al. (2019) supported the abovementioned statement, where even higher inclusion, i.e., from 9% to 18.5% did not negatively affect the profit indexes. It is crucial from a practical point of view, where the price of insect meals cannot compete with the commonly used feed materials. However, the unification of prices allows emphasizing the additional properties of insect products in terms of, e.g., the possibility of significantly reducing global warming potential and land use through the implementation of waste-fed larvae in pig diets (van Zanten et al., 2018).

6.2. Functional properties of insects in pig nutrition

Further benefits related to invertebrate usage in swine diets have a positive impact on the immune response. Yu et al. (2020a) showed that the 2% inclusion of *H. illucens* full-fat meals by 28 d of the trial decreased proinflammatory (interferon- γ , *IFN- γ*) and enhanced the concentration of anti-inflammatory (interleukin-10, *IL-10*) factors in weaning piglets. This is in agreement with the results of Yu et al. (2020b), who found downregulated mRNA expression of *TNF- α* and upregulated *IL-10* (2% *H. illucens* addition by 28 d), as well as Yu et al. (2019b), where supplementation of 4% *H. illucens* larvae meal (48-d trial) reduced toll-like receptor 4 (*TLR-4*) and *IFN- γ* gene expression and enhanced *IL-10*. Furthermore, the addition of 4% *H. illucens* to the finishing pig diets resulted in the upregulation of intestinal barrier genes, i.e., mucin-1, *ZO-1*, and occludin (Yu et al., 2019b). Nonetheless, Choi et al. (2020) and Ao et al. (2020) did not observe any immune response of weaning piglets (*TNF- α* , interleukin-1 β [*IL-1 β*], *IL-6*, immunoglobulin G [*IgG*]) during *H. illucens* meal administration up to 3% by 14 d of the trial or *IgG* and lymphocyte concentrations after 1% or 2% *T. molitor* application during 35-d experiment. This is supported by Ko et al. (2020), who did not notice any changes (during the 28-d test) in terms of *IL-1 β* , *TNF- α* , or *IL-6* concentrations after partial or total replacement of fishmeal by *T. molitor* larvae meal (phase 1: up to 5%; phase 2: up to 3%) in weaning pig diets. Moreover, it is well known that the immunological response relates to GIT microbiota homeostasis, and frequently, the GIT is defined as the largest “immune organ” in the animal body. Thus, it is no surprise that the administration of *H. illucens* larvae meal (5% by 61 d of the experiment) as a product rich in chitin, lauric acid, and AMPs to swine enhanced beta diversity in the ceca (Biasato et al., 2020). Furthermore, the proliferation of microbial populations engaged in polysaccharide fermentation, as well as short-chain fatty acids and consequently supporting epithelial cell metabolism production, i.e., *Blautia*, *Coprococcus*, *Eubacterium*, *Prevotella*, *Roseburia*, and *Ruminococcaceae*, was enhanced in weaning piglets (Biasato et al., 2020). Additionally, after *H. illucens* larvae meal inclusion, increased neutral mucin production was found in the small intestine to prevent intestinal pathobiota access to the epithelium. This is supported by Yu et al. (2019b), who reported a positive increase in butyrate-producing bacteria in the colon, as well as the limitation of pathogenic colon bacteria occurrence, i.e., *Streptococcus*. Moreover, the main effect of *H. illucens* inclusion on the weaning piglet GIT microbiota was observed in the colon, while the ileal microecosystem was particularly changed in terms of enhanced *Lactobacillus* and *Bifidobacterium* populations. In contrast to the colon, Firmicutes, *Ruminococcus*, *Clostridium* cluster IV, and *Prevotella* were significantly increased (Yu et al., 2020b). It should be highlighted that the studies conducted on the dietary supplementation of AMPs have indicated that synthetic analogs of hybrid cecropin-magainin (90 mg/kg AMP-A3 and 40 to 60 mg/kg AMP-P5) have a positive effect on the growth performance, fecal microbiota, and intestinal morphology of weaning piglets during 28-d long experiments (Yoon et al., 2012, 2013, 2014). Furthermore, the results of Crosbie et al. (2021) clearly showed that the substitution of animal origin protein up to 50% by full-fat *H. illucens* larvae meal (throughout the 42-d trial) can be as efficient as the addition of antibiotic growth promotor, i.e., 220 mg of aureomycin per kg of complete feed, in the scope of growth performance results, immune response, and gut health in nursery pigs. Moreover, a study performed in vivo indicated that an AMP complex provided as a mixture of lactoferrin, cecropin, defensin and plectasin (2 g, and

3 g/kg feed for a 32-d period) improved growth performance, reduced diarrhea and increased the survival rate of weaned pigs (Xiong et al., 2014). That the compounds containing insect AMP complexes have an advantage over individual peptide and small molecule antibiotics has also been proven in research performed in vitro (Chernysh et al., 2015). The application of insect meal providing a variety of different biologically active components to animal feed may give rise to new possibilities in animal production.

In conclusion, due to the positive effect of the inclusion of various invertebrates in pig diets at all stages of the rearing process on growth performance, final product quality, GIT health, and immune response, without economic losses, there is a premise to implement these environmentally friendly products in practical swine nutrition.

7. Insects in aquaculture

Aquaculture is one of the fastest-growing branches of animal products intended for food market purposes. According to WHO and FAO predictions and scientific literature, fish meat will play a crucial role in meeting the growing needs for livestock protein (FAO, 2020; FAO/WHO, 2018; Vianna et al., 2020). However, consumers' criticism of aquaculture production concerns feed components, and most of them are not environmentally sustainable. Currently, the dominant protein and fat sources in fish feed are fish meals and oils, soybean meals and oils, and protein isolates. In the case of fishmeal and fish oil, the main disadvantage is the overfishing of seas and oceans. Up to 30% of the caught fish are used for animal feed production, while 90% of this value could be used for human consumption (Olsen and Hasan, 2012). Additionally, this situation leads to competition between the food market and animal production, and the erosion of natural sources of fish also affects rapidly increasing fish meal prices. While discussing plant sources of protein and fats in fish nutrition, mainly various soybean derivatives, their impact on biodiversity loss, tropical forest destruction, and large-scale pesticide use should be emphasized. In addition, progressively, many customers seem to be opposite to the usage of genetically modified products such as soybean meal (Costa-Pierce, 2010).

In the case of aquaculture production, the main interests in Europe are focused on salmonid fish. According to the Publications Office of the European Union report (EUMOFA, 2020), the 2 leading species produced in the EU are Atlantic salmon (*Salmo salar*) and rainbow trout (*Oncorhynchus mykiss*), whose total EU farmed production value is almost 40%. Due to the developing problem of using fishmeal as the main protein source in salmonid feed, scientific teams are looking for alternatives. Some of them are focused mainly on plant-derived compounds and proteins and their impact on the growth performance, feed utilization, and physiological response of fish (Bruce et al., 2017; Clarkson et al., 2017; Greiling et al., 2018). However, the substitution of fishmeal by plant ingredients in salmonid diets can lead to a reduction in feed utilization, which results in poor growth performance (Wacyk et al., 2012). Moreover, the effect of soybean addition to feeding on the occurrence of distal enteritis and deterioration of reproductive parameters has already been reported (Lazzarotto et al., 2015).

7.1. Insect meals in salmonid nutrition

Carnivorous fish salmonids already count insects as a part of their diets in the natural environment (Henry et al., 2015). Depending on the salmonid species, fishmeal substitution can reach different levels, with or without various effects on growth performance and feed utilization (Table 6). According to Belghit

et al. (2019), even 100% replacement of fishmeal with partially defatted *H. illucens* meal is possible without any adverse effect on growth performance or feed utilization of Atlantic salmon. The partially defatted meal did not cause any adverse effects on most physiological parameters related to the functioning of the GIT, such as apparent digestibility coefficients (ADCs) of nutrients, digestive enzyme activity, or total bile acid levels. Divergent results were reported by Weththasinghe et al. (2021), where the 25% substitution of fishmeal with *H. illucens* meal resulted in a lower final body weight (FBW), specific growth rate (SGR), protein efficiency ratio (PER), and higher FCR. It is important to emphasize that this experiment was conducted using full-fat meals. While the ADC of CP was not affected by insect inclusion in salmon diets, decreases in crude fat and tyrosine digestibility were observed in the 12.5% and 25% substitution groups. A decrease in the lipid efficiency ratio (LER) was observed in all groups fed insect meals. Experiments conducted on rainbow trout presented different possible substitution levels in the case of growth performance and feed utilization. Some of the literature pointed to no adverse effect on those parameters in substitution fishmeal level by *H. illucens* up to 30% (Józefiak et al., 2019; Terova et al., 2019), while others reported several negative effects on digestibility of nutrients and feed utilization (Melenchón et al., 2021; Renna et al., 2017; Stadlander et al., 2017); however, the growth performance was still not disturbed. This effect is observed further with the usage of different insect species (Józefiak et al., 2019; Melenchón et al., 2021) but also in experiments conducted on sea trout (*Salmo trutta m. trutta*) fed diets containing full-fat and hydrolyzed full-fat meals obtained from Tenebrionidae family insects (Hoffmann et al., 2020; Mikołajczak et al., 2020). In most of the scientific literature, any disturbance in the digestibility of nutrients that occurs in fish fed insect meals is explained by the presence of chitin in the exoskeleton of insects. Even in the healthy GIT characterized by good homeostasis and chitinase activity, chitin digestibility will not be effective (Renna et al., 2017), and the presence of chitin can be correlated with lower protein digestion (Marono et al., 2015). Furthermore, it can be considered a low-energy filler (Karlsen et al., 2017), and both of these observations can be crucial limiting factors due to the ultimate effect on poor growth performance.

7.2. Insect fat in salmonid nutrition

From the production point of view and the interests of future customers, the effect of insect inclusion in salmonid diets on fillet chemical composition and quality is crucial, especially since fish are considered healthy meat due to their valuable fatty acids composition that prevents coronary heart diseases. In the current literature, this impact has been investigated. Renna et al. (2017) reported that the effect of the addition of *H. illucens* in rainbow trout diets on the composition of fish meat is indeed present; however, this impact is still within the normal ranges and does not cause any deviations that could be potentially harmful to humans. However, Melenchón et al. (2021) proved that the inclusion of *T. molitor* in rainbow trout diets can affect meat quality due to an increase in MUFAs and *n*-6 fatty acids, together with a decrease in *n*-3. The possibility of negative effects of insect usage in livestock nutrition on meat quality leads to new scientific area exploration – to examine the effect of different diets on insects' fatty acids composition. Ewald et al. (2020) reported that modification of the fatty acid composition of *H. illucens* through its diet is possible; however, it seems to have some limitations, especially in SFA and MUFA contents. Notwithstanding, Oonincx et al. (2020) proved that the substitution of flaxseed oil in edible insect diets can improve their nutritional quality, especially in *n*-3 content.

Table 6
Effect of various invertebrate meals used as an alternative to commonly used feed materials in salmonid nutrition on their productivity and physiological traits.

Insect species	Replaced compounds	Processing form	Species	Substitution level	Main results	Reference
<i>Hermetia illucens</i>	Fishmeal	Partially defatted	Atlantic salmon (<i>Salmo salar</i>)	33%; 66%; 100%	The effect on whole fish fatty acids composition. Increase in glucose concentration in blood plasma in the group with 66% of substitution.	Belghit et al. (2019)
<i>H. illucens</i>	Protein compounds: Fishmeal, soy protein concentrate, corn gluten, faba bean	Full-fat meal	Atlantic salmon (<i>S. salar</i>)	6.25%; 12.5%; 25%	The decrease in final body weight and specific growth rate, while an increase in FCR in the 25% replacement group. A decrease in 12.5 and 25% groups in the case of crude fat and tyrosine apparent digestibility coefficient (ADC) was observed. An increase in starch digestibility in the 25% group. The lower protein efficiency ratio, apparent lipid, and energy retention in the 25% group. The decrease in lipid efficiency ratio in all groups fed with insects.	Weththasinghe et al. (2021)
<i>H. illucens</i>	Fishmeal	Full-fat paste Defatted	Rainbow trout (<i>Oncorhynchus mykiss</i>)	3.7%; 6.7% 46%	No detrimental effects. A decrease in protein efficiency ratio (PER) and protein productive value.	Stadtlander et al. (2017)
<i>H. illucens</i>	Fishmeal	Partially defatted	Rainbow trout (<i>O. mykiss</i>)	10%; 20%; 30%	Modulation of gastrointestinal tract microbiota.	Terova et al. (2019)
<i>H. illucens</i>	Fishmeal	Partially defatted	Rainbow trout (<i>O. mykiss</i>)	25%; 50%	The decrease in ADC of dry matter and crude protein in the 50% group. Strong impact on fatty acids composition of fish filets.	Renna et al. (2017)
<i>H. illucens</i>	Fishmeal	Full-fat	Rainbow trout (<i>O. mykiss</i>)	15%; 30%	The decrease in FCR values in both substitution groups. The modulation of digestive enzymes and hepatic enzymes activity. The effect on immune parameters in plasma. The impact on fatty acids composition of fish filets.	Melenchón et al. (2021)
<i>Tenebrio molitor</i>					Lower ADC of protein in 30% substitution group. Higher value of viscerosomatic index (VSI) in 30% substitution group. The modulation of digestive enzymes and hepatic enzymes activity. The effect on immune parameters in plasma. The impact on fatty acids composition of fish filets.	
<i>H. illucens</i>	Fishmeal	Full-fat meal	Rainbow trout (<i>O. mykiss</i>)	30%	Impact on intestinal microbiota—lower concentration of <i>Clostridium coccoides</i> , and <i>Lactobacillus/Enterococcus</i> sp.	Józefiak et al. (2019)
<i>T. molitor</i>				41%	The decrease in villus height. Impact on intestinal microbiota—increase in concentration in all analyzed bacteria.	
<i>Gryllodes sigillatus</i>				48%	A decrease in SGR and an increase in FCR. The decrease in villus height and mucosa thickness. Impact on intestinal microbiota—increase in concentration in most analyzed bacteria populations.	
<i>Blatta lateralis</i>				42%	Higher results of body weight gain. The increase in villus height and mucosa thickness. Impact on intestinal microbiota—increase in concentration in most analyzed bacteria.	

Table 6 (continued)

Insect species	Replaced compounds	Processing form	Species	Substitution level	Main results	Reference
<i>T. molitor</i>	Fishmeal	Full-fat meal Hydrolyzed full-fat meal at 0.5% endopeptidase	Sea trout (<i>Salmo trutta m. trutta</i>)	10%	No detrimental effects. No detrimental effects.	Hoffmann et al. (2020)
<i>T. molitor</i>	Fishmeal	Hydrolyzed full-fat meal at 1.0% endopeptidase	Sea trout (<i>S. trutta m. trutta</i>)	42%	A decrease in PER and effect on serum biochemistry composition. The impact on the microbiota of digesta—lower concentration of <i>Carnobacterium</i> spp. and <i>Lactobacillus</i> group.	Mikołajczak et al. (2020)
<i>Zophobas morio</i>				44%	A decrease in PER. The increase in hepatosomatic index (HSI), viscerosomatic index (VSI), and liver lipid. The influence on serum biochemistry composition. The effect on the gut microbiota by reducing pathogenic bacteria—lower concentration of <i>Aeromonas</i> spp., <i>Carnobacterium</i> spp. and <i>Enterococcus</i> spp.	

7.3. Functional properties of insects in fish nutrition

Considering insects as a component in salmonid feeds, the effect on the microbiota of the GIT should be discussed. Several studies proved the positive effect of insect meal inclusion in salmonid fish diets due to the reduced concentration of pathogenic bacteria and an increasing number of health-promoting bacterial species (Józefiak et al., 2019; Mikołajczak et al., 2020; Terova et al., 2019). This impact should be explained by three main insect features, i.e., C12:0 antimicrobial properties (mentioned above), the presence of chitin, and AMPs. Despite the probable negative effect of chitin on nutrient digestion, chitin can be further considered a factor modulating the microbiome of the GIT. According to Askarian et al. (2012), chitin inclusion in the Atlantic salmon diet at the level of 5% led to decreases in the concentrations of *Bacillus* spp., *Lactobacillus* spp., *Pseudomonas* spp., and *Staphylococcus* spp. Therefore, chitin and its derivatives have potential as prebiotics and immunostimulants, and as their source, insect meals can also provide this effect. Second, AMPs additionally stimulate these effects. It is well documented that AMPs present in insects are characterized by activity against a wide spectrum of pathogenic bacteria, such as *S. aureus*, *L. monocytogenes*, and *S. typhimurium* (Yi et al., 2014).

8. Conclusion

In the available literature, invertebrate-derived products are presented as a natural and sustainable source of protein and energy for various animal species. The latest data confirm the possibility of their implementation in animal diets with mostly positive effects on growth performance and organism response. However, due to the low uniformity of insect products globally, i.e., 1) the usage of various technologies, which induces a need for different feeding system applications; 2) the usage of food waste in invertebrate production, which differs in the case of nutritive value; 3) the lack of nutrient requirement recommendations for commonly reared larval species; 4) and, last but not least, the divergent processing techniques of larvae, play a crucial role in terms of the quality of the

final feed material and consequently cause different productivity and health effects in insect-fed animals. Consequently, to increase the efficiency of the insect larvae, as well as further livestock, aquaculture production, and pet conditions, the detailed nutrient requirements and biomass process technique parameters for economically justified species should be evaluated in the future.

Author contributions

Bartosz Kierończyk: Conceptualization, Investigation, Writing - Original Draft, Visualization; **Mateusz Rawski:** Conceptualization, Investigation, Writing - Original Draft; **Zuzanna Mikołajczak:** Investigation, Writing - Original Draft; **Natalia Homska:** Investigation, Writing - Original Draft; **Jan Jankowski:** Writing - Review & Editing, Supervision; **Katarzyna Ognik:** Writing - Review & Editing, Supervision; **Agata Józefiak:** Investigation, Writing - Review & Editing, Visualization; **Jan Mazurkiewicz:** Writing - Review & Editing, Supervision; **Damian Józefiak:** Conceptualization, Writing - Review & Editing, Supervision.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, and there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the content of this paper.

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Appendix. supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.aninu.2022.06.015>.

References

- Adebayo HA, Kembabanta KA, Ogbogu SS, Elechi MC, Obe MT. Comparative assessment of developmental parameters, proximate analysis and mineral compositions of black soldier fly (*Hermetia illucens*) prepupae reared on organic waste substrates. *Int J Trop Insect Sci* 2021;41:1953–9. <https://doi.org/10.1007/s42690-020-00404-4>.
- Ali Mohammadie Kojour M, Jang HA, Edosa TT, Keshavarz M, Kim BB, Bae YM, et al. Identification, in silico characterization, and expression analysis of *Tenebrio molitor* Cecropin-2. *Entomol Res* 2021;51:74–82. <https://doi.org/10.1111/1748-5967.12476>.
- Allegretti G, Talamini E, Schmidt V, Bogorni PC, Ortega E. Insect as feed: an emergy assessment of insect meal as a sustainable protein source for the Brazilian poultry industry. *J Clean Prod* 2018;171:403–12.
- Altmann BA, Neumann C, Rothstein S, Liebert F, Mörlein D. Do dietary soy alternatives lead to pork quality improvements or drawbacks? A look into micro-alga and insect protein in swine diets. *Meat Sci* 2019;153:26–34. <https://doi.org/10.1016/j.meatsci.2019.03.001>.
- Ao X, Kim IH. Effects of dietary dried mealworm (*Ptecticus tenebrifer*) larvae on growth performance and nutrient digestibility in weaning pigs. *Livest Sci* 2019;230:103815.
- Ao X, Yoo JS, Wu ZL, Kim IH. Can dried mealworm (*Tenebrio molitor*) larvae replace fish meal in weaned pigs? *Livest Sci* 2020;239. <https://doi.org/10.1016/j.livsci.2020.104103>.
- Askarian F, Zhou Z, Olsen RE, Sperstad S, Ringø E. Culturable autochthonous gut bacteria in Atlantic salmon (*Salmo salar* L.) fed diets with or without chitin. Characterization by 16S rRNA gene sequencing, ability to produce enzymes and *in vitro* growth inhibition of four fish pathogens. *Aquaculture* 2012;326:1–8.
- Ballitoc DA, Sun S. Ground yellow mealworms (*Tenebrio molitor* L.) feed supplementation improves growth performance and carcass yield characteristics in broilers. *Open Sci Repos Agric* 2013;18:e23050425.
- Barragan-Fonseca KB, Dicke M, Van Loon JJA. Influence of larval density and nutrient concentration on performance and body protein and fat composition of *Hermetia illucens* larvae. *Entomol Exp Appl* 2018;166:761–71.
- Barragan-Fonseca KB, Gort G, Dicke M, Van Loon JJA. Effects of dietary protein and carbohydrate on life-history traits and body protein and fat contents of the black soldier fly *Hermetia illucens*. *Physiol Entomol* 2019;44:148–59.
- Barragan-Fonseca KB, Gort G, Dicke M, van Loon JJA. Nutritional plasticity of the black soldier fly (*Hermetia illucens*) in response to artificial diets varying in protein and carbohydrate concentrations. *J Insects as Food Feed* 2021;7:51–61.
- Bax M-L, Aubry L, Ferreira C, Daudin J-D, Gatellier P, Rémond D, et al. Cooking temperature is a key determinant of *in vitro* meat protein digestion rate: investigation of underlying mechanisms. *J Agric Food Chem* 2012;60:2569–76.
- Behmer ST. Insect herbivore nutrient regulation. *Annu Rev Entomol* 2009;54:165–87.
- Behrendorff L, Leung LK-P, McKinnon A, Hanger J, Belonje G, Tapply J, et al. Insects for breakfast and whales for dinner: the diet and body condition of dingoes on Fraser Island (K'gari). *Sci Rep* 2016;6:23469. <https://doi.org/10.1038/srep23469>.
- Belghit I, Liland NS, Gjesdal P, Biancarosa I, Menchetti E, Li Y, et al. Black soldier fly larvae meal can replace fish meal in diets of sea-water phase Atlantic salmon (*Salmo salar*). *Aquaculture* 2019;503:609–19.
- Beniers JJA, Graham RI. Effect of protein and carbohydrate feed concentrations on the growth and composition of black soldier fly (*Hermetia illucens*) larvae. *J Insects as Food Feed* 2019;5:193–9.
- Benzerthi A, Kierończyk B, Rawski M, Józefiak A, Kozłowski K, Jankowski J, et al. *Tenebrio molitor* and *Zophobas morio* full-fat meals in broiler chicken diets: effects on nutrients digestibility, digestive enzyme activities, and cecal microbiome. *Animals* 2019a;9:1128. <https://doi.org/10.3390/ani9121128>.
- Benzerthi A, Kierończyk B, Rawski M, Kotodziejski P, Bryszak M, Józefiak D. Insect oil as an alternative to palm oil and poultry fat in broiler chicken nutrition. *Animals* 2019b;9:116.
- Benzerthi A, Kierończyk B, Kotodziejski P, Pruszyńska-Oszmątek E, Rawski M, Józefiak D, et al. *Tenebrio molitor* and *Zophobas morio* full-fat meals as functional feed additives affect broiler chickens' growth performance and immune system traits. *Poult Sci* 2020a;99:196–206. <https://doi.org/10.3382/ps/pez450>.
- Benzerthi A, Kierończyk B, Rawski M, Mikołajczak Z, Urbański A, Nogowski L, et al. Insect fat in animal nutrition: a review. *Ann Anim Sci* 2020b;20:1217–40. <https://doi.org/10.2478/aoas-2020-0076>.
- Bessa LW, Pieterse E, Sigge G, Hoffman LC. Insects as human food; from farm to fork. *J Sci Food Agric* 2020;100:5017–22.
- Beynen AC. Hypoallergenic cat foods. *Dier-en-Arts* 2020;10:255–7.
- Biasato I, Renna M, Gai F, Dabbou S, Meneguz M, Perona G, et al. Partially defatted black soldier fly larva meal inclusion in piglet diets: effects on the growth performance, nutrient digestibility, blood profile, gut morphology and histological features. *J Anim Sci Biotechnol* 2019;10:1–11. <https://doi.org/10.1186/s40104-019-0325-x>.
- Biasato I, Ferrocino I, Colombino E, Gai F, Schiavone A, Coccolin L, et al. Effects of dietary *Hermetia illucens* meal inclusion on cecal microbiota and small intestinal mucin dynamics and infiltration with immune cells of weaned piglets. *J Anim Sci Biotechnol* 2020;11:1–11. <https://doi.org/10.1186/s40104-020-00466-x>.
- Böhm TM, Klinger CJ, Udraitė L, Müller RS. The beneficial effects of an insect protein based elimination diet on clinical signs of food allergy in dogs. *Allergy* 2017;72:601.
- Böhm TMSA, Klinger CJ, Gedon N, Udraitė L, Hiltenkamp K, Mueller RS. Effect of an insect protein-based diet on clinical signs of dogs with cutaneous adverse food reactions. *Tierarztl Prax Ausg K Kleintiere Heimtiere* 2018;46:297–302.
- Bonelli M, Bruno D, Brilli M, Gianfranceschi N, Tian L, Tettamanti G, et al. Black soldier fly larvae adapt to different food substrates through morphological and functional responses of the midgut. *Int J Mol Sci* 2020;21:1–27. <https://doi.org/10.3390/ijms21144955>.
- Borrelli L, Varriale L, Dipinetto L, Pace A, Menna LF, Fioretti A. Insect derived lauric acid as promising alternative strategy to antibiotics in the antimicrobial resistance scenario. *Front Microbiol* 2021;12:1–7. <https://doi.org/10.3389/fmicb.2021.620798>.
- Bosch G, Vervoort JJM, Hendriks WH. *In vitro* digestibility and fermentability of selected insects for dog foods. *Anim Feed Sci Technol* 2016;221:174–84. <https://doi.org/10.1016/j.anifeedsci.2016.08.018>.
- Bruce KJ, Karr-Lilienthal LK, Zinn KE, Pope LL, Mahan DC, Fastinger ND, et al. Evaluation of the inclusion of soybean oil and soybean processing by-products to soybean meal on nutrient composition and digestibility in swine and poultry. *J Anim Sci* 2006;84:1403–14.
- Bruce TJ, Sindelar SC, Voorhees JM, Brown ML, Barnes ME. Performance and immunological responses of rainbow trout (*Oncorhynchus mykiss*) fed bio-processed plant-based proteins. *Aquac Nutr* 2017;23:1160–8.
- Bukkens SGF. The nutritional value of edible insects. *Ecol Food Nutr* 1997;36:287–319. <https://doi.org/10.1080/03670244.1997.9991521>.
- Caligiani A, Marseglia A, Sorci A, Bonzanini F, Lolli V, Maistrello L, et al. Influence of the killing method of the black soldier fly on its lipid composition. *Food Res Int* 2019;116:276–82.
- Cammack JA, Tomberlin JK. The impact of diet protein and carbohydrate on select life-history traits of the black soldier fly *Hermetia illucens* (L.) (Diptera: Stratiomyidae). *Insects* 2017;8:56.
- Chae J-H, Kurokawa K, So Y-I, Hwang HO, Kim M-S, Park J-W, et al. Purification and characterization of tenecin 4, a new anti-Gram-negative bacterial peptide, from the beetle *Tenebrio molitor*. *Dev Comp Immunol* 2012;36:540–6. <https://doi.org/10.1016/j.dci.2011.09.010>.
- Chernysh S, Gordya N, Suborova T. Insect antimicrobial peptide complexes prevent resistance development in bacteria. *PLoS One* 2015;10:e0130788. <https://doi.org/10.1371/journal.pone.0130788>.
- Chia SY, Tanga CM, Osuga IM, Alaru AO, Mwangi DM, Githinji M, et al. Effect of dietary replacement of fishmeal by insect meal on growth performance, blood profiles and economics of growing pigs in Kenya. *Animals* 2019;9:705. <https://doi.org/10.3390/ani9100705>.
- Chia SY, Tanga CM, Osuga IM, Alaru AO, Mwangi DM, Githinji M, et al. Black soldier fly larval meal in feed enhances growth performance, carcass yield and meat quality of finishing pigs. *J Insects as Food Feed* 2021;2:1–16. <https://doi.org/10.3920/jiff2020.0072>.
- Choi SC, Ingale SL, Kim JS, Park YK, Kwon IK, Chae BJ. An antimicrobial peptide-A3: effects on growth performance, nutrient retention, intestinal and faecal microflora and intestinal morphology of broilers. *Br Poult Sci* 2013a;54:738–46. <https://doi.org/10.1080/00071668.2013.838746>.
- Choi SC, Ingale SL, Kim JS, Park YK, Kwon IK, Chae BJ. Effects of dietary supplementation with an antimicrobial peptide-P5 on growth performance, nutrient retention, excreta and intestinal microflora and intestinal morphology of broilers. *Anim Feed Sci Technol* 2013b;185:78–84. <https://doi.org/10.1016/j.anifeedsci.2013.07.005>.
- Choi Y-H, Yoon S-Y, Jeon S-M, Lee J-Y, Oh S-M, Lee S-H, et al. Effects of different levels of *Hermetia illucens* on growth performance and nutrient digestibility in weaning pigs. *J Korea Acad Coop Soc* 2019;20:255–61.
- Choi Y, Jo-eun Kim, Jung H, Cho ES, Kim D, Jin-soo Kim. Effects of *Hermetia illucens* supplementation on fecal score, blood profiles, immune response and small intestinal morphology in weaned pigs. *J Korea Acad Coop Soc* 2020;21:392–9. <https://doi.org/10.5762/KAIS.2020.21.4.392>.
- Clarkson M, Migaud H, Metochis C, Vera LM, Leeming D, Tocher DR, et al. Early nutritional intervention can improve utilisation of vegetable-based diets in diploid and triploid Atlantic salmon (*Salmo salar* L.). *Br J Nutr* 2017;118:17–29.
- Costa-Pierce BA. Sustainable ecological aquaculture systems: the need for a new social contract for aquaculture development. *Mar Technol Soc J* 2010;44:88–112.
- Crosbie M, Zhu C, Shoveller AK, Huber LA. Standardized ileal digestible amino acids and net energy contents in full fat and defatted black soldier fly larvae meals (*Hermetia illucens*) fed to growing pigs. *Transl Anim Sci* 2020;4:1–10. <https://doi.org/10.1093/tas/txaa104>.
- Crosbie M, Zhu C, Karow NA, Huber L. The effects of partially replacing animal protein sources with full fat black soldier fly larvae meal (*Hermetia illucens*) in nursery diets on growth performance, gut morphology, and immune response of pigs. *Transl Anim Sci* 2021;5:1–11.
- Cullere M, Schiavone A, Dabbou S, Gasco L, Zotte AD. Meat quality and sensory traits of finisher broiler chickens fed with black soldier fly (*Hermetia illucens* L.) larvae fat as alternative fat source. *Animals* 2019;9:1–15. <https://doi.org/10.3390/ani9040140>.

- Dabbou S, Ferrocino I, Gasco L, Schiavone A, Trocino A, Xiccato G, et al. Antimicrobial effects of black soldier fly and yellow mealworm fats and their impact on gut microbiota of growing rabbits. *Animals* 2020;10:1–19. <https://doi.org/10.3390/ani10081292>.
- Daniele B, Marco B, Francesca DF, Ilaria DL, Gianluca T, Morena C, et al. The intestinal microbiota of *Hermetia illucens* larvae is affected by diet and shows a diverse composition in the different midgut regions. *Appl Environ Microbiol* 2022;85. <https://doi.org/10.1128/AEM.01864-18>. e01864-18.
- Dankwa D, Oddoye EOK, Mzamo KB. Preliminary studies on the complete replacement of fishmeal by house-fly-larvae-meal in weaner pig diets: effects on growth rate, carcass characteristics, and some blood constituents. *Ghana J Agric Sci* 2000;33:223–7.
- de Souza Vilela J, Andronicos NM, Kolakshyapati M, Hilliar M, Sibanda TZ, Andrew NR, et al. Black soldier fly larvae in broiler diets improve broiler performance and modulate the immune system. *Anim Nutr* 2021;7:695–706. <https://doi.org/10.1016/j.aninu.2020.08.014>.
- Delicato C, Schouteten JJ, Dewettinck K, Gellynck X, Tzompa-Sosa DA. Consumers' perception of bakery products with insect fat as partial butter replacement. *Food Qual Prefer* 2020;79:103755. <https://doi.org/10.1016/j.foodqual.2019.103755>.
- Driemeyer H. Evaluation of black soldier fly (*Hermetia illucens*) larvae as an alternative protein source in pig creep diets in relation to production, blood and manure microbiology parameters [Master Degree Thesis Dissertation]. Stellenbosch University; 2016.
- Egan BA, Addo-Bediako A, Masoko P, Mphosi M, Olivier PAS, Toms R, et al. Nutritional significance of the edible insect, *Hemijana variegata* Rothschild (Lepidoptera: Eupterotidae), of the Blouberg region, Limpopo, South Africa. *Afr Entomol* 2014;22:15–23.
- El-Hack A, Mohamed E, Shafi ME, Alghamdi WY, Abdelnour SA, Shehata AM, et al. Black soldier fly (*Hermetia illucens*) meal as a promising feed ingredient for poultry: a comprehensive review. *Agriculture* 2020;10:339.
- Elhag O, Zhou D, Song Q, Soomro AA, Cai M, Zheng L, et al. Screening, expression, purification and functional characterization of novel antimicrobial peptide genes from *Hermetia illucens* (L.). *PLoS One* 2017;12:e0169582.
- EUMOFA - European Market Observatory for Fisheries and Aquaculture Products, The EU Fish Market. https://www.eumofa.eu/documents/20178/415635/EN_The+EU+fish+market_2020.pdf/fe6285bb-544e-ac1a-e213-6fd6f64d0d85?t=1604671147068. [Accessed 20 July 2022].
- Ewald N, Vidakovic A, Langeland M, Kiessling A, Sampels S, Lalander C. Fatty acid composition of black soldier fly larvae (*Hermetia illucens*) – possibilities and limitations for modification through diet. *Waste Manag* 2020;102:40–7. <https://doi.org/10.1016/j.wasman.2019.10.014>.
- FAO. The State of World Fisheries and Aquaculture 2020. Sustainability in action. Rome. <https://www.fao.org/3/ca9229en/ca9229en.pdf>. [Accessed 20 July 2022].
- FAO/WHO. The State of World Fisheries and Aquaculture 2018 – Meeting the sustainable development goals. Rome. <https://www.fao.org/3/i9540en/i9540en.pdf>. [Accessed 20 July 2022].
- Freel TA, McComb A, Koutsos EA. Digestibility and safety of dry black soldier fly larvae meal and black soldier fly larvae oil in dogs. *J Anim Sci* 2021;99:1–8. <https://doi.org/10.1093/jas/skab047>.
- Gasco L, Finke M, van Huis A. Can diets containing insects promote animal health? *J Insects as Food Feed* 2018;4:1–4. <https://doi.org/10.3920/JIFF2018.X001>.
- Gasco L, Dabbou S, Gai F, Brugiapaglia A, Schiavone A, Birolo M, et al. Quality and consumer acceptance of meat from rabbits fed diets in which soybean oil is replaced with black soldier fly and yellow mealworm fats. *Animals* 2019;9:629. <https://doi.org/10.3390/ani9090629>.
- Gasco L, Józefiak A, Henry M. Beyond the protein concept: health aspects of using edible insects on animals. *J Insects as Food Feed* 2020;1–28. <https://doi.org/10.3920/jiff2020.0077>.
- Gold M, Cassar CM, Zurbrügg C, Kreuzer M, Boulous S, Diener S, et al. Biowaste treatment with black soldier fly larvae: increasing performance through the formulation of biowastes based on protein and carbohydrates. *Waste Manag* 2020;102:319–29.
- Greiling AM, Schwarz C, Gierus M, Rodehutsord M. Pumpkin seed cake as a fishmeal substitute in fish nutrition: effects on growth performance, morphological traits and fillet colour of two freshwater salmonids and two catfish species. *Arch Anim Nutr* 2018;72:239–59.
- Håkenåsen IM, Grepperud GH, Hansen JØ, Øverland M, Ånestad RM, Mydland LT. Full-fat insect meal as a protein and energy source for weaned piglets: effects on growth performance, nutrient digestibility, gastrointestinal function and microbiota. *Research Square* 2020;1–37. <https://doi.org/10.21203/rs.3.rs-61552/v1>.
- Henry M, Gasco L, Piccolo G, Fountoulaki E. Review on the use of insects in the diet of farmed fish: Past and future. *Anim Feed Sci Technol* 2015;203:1–22. <https://doi.org/10.1016/j.anifeeds.2015.03.001>.
- Herrero J, García-Serrano A, Couto S, Ortuño VM, García-González R. Diet of wild boar *Sus scrofa* L. and crop damage in an intensive agroecosystem. *Eur J Wildl Res* 2006;52:245–50. <https://doi.org/10.1007/s10344-006-0045-3>.
- Heuel M, Sandrock C, Leiber F, Mathys A, Gold M, Zurbrügg C, et al. Black soldier fly larvae meal and fat can completely replace soybean cake and oil in diets for laying hens. *Poult Sci* 2021;100:101034. <https://doi.org/10.1016/j.psj.2021.101034>.
- van Heugten E, Martínez G, McComb A, Koutsos E. 285 Black soldier fly (*Hermetia illucens*) larvae oil improves growth performance of nursery pigs. *J Anim Sci* 2019;97:118.
- Hoffmann L, Rawski M, Nogales-Merida S, Mazurkiewicz J. Dietary inclusion of *Tenebrio molitor* meal in sea trout larvae rearing: effects on fish growth performance, survival, condition, and GIT and liver enzymatic activity. *Ann Anim Sci* 2020;20:579–98.
- Hong Y, Zhou J, Yuan MM, Dong H, Cheng GQ, Wang YJ, et al. Dietary supplementation with housefly (*Musca domestica*) maggot meal in growing beagles: hematology, serum biochemistry, immune responses and oxidative damage. *Ann Anim Sci* 2020;20:1351–64. <https://doi.org/10.2478/aoas-2020-0045>.
- Huang C, Feng W, Xiong J, Wang T, Wang W, Wang C, et al. Impact of drying method on the nutritional value of the edible insect protein from black soldier fly (*Hermetia illucens* L.) larvae: amino acid composition, nutritional value evaluation, in vitro digestibility, and thermal properties. *Eur Food Res Technol* 2019;245:11–21. <https://doi.org/10.1007/s00217-018-3136-y>.
- Huang Y, Yu Y, Zhan S, Tomberlin JK, Huang D, Cai M, et al. Dual oxidase Duox and Toll-like receptor 3 TLR3 in the Toll pathway suppress zoonotic pathogens through regulating the intestinal bacterial community homeostasis in *Hermetia illucens* L. *PLoS One* 2020;15:e0225873. <https://doi.org/10.1371/journal.pone.0225873>.
- Hughes J, Macdonald DW. A review of the interactions between free-roaming domestic dogs and wildlife. *Biol Conserv* 2013;157:341–51.
- Ibáñez MA, de Blas C, Cámara L, Mateos GG. Chemical composition, protein quality and nutritive value of commercial soybean meals produced from beans from different countries: a meta-analytical study. *Anim Feed Sci Technol* 2020;267:114531. <https://doi.org/10.1016/j.anifeeds.2020.114531>.
- Ibitoye OS, Kolejo OS, Muritala DS, Ibitoye OS, Kolejo OS, Muritala DS, et al. Insect meal an alternative protein source in animal food. *Int J Food Nutr* 2019;3:70–8.
- Ipema AF, Bokkers EAM, Gerrits WJJ, Kemp B, Bolhuis JE. Providing live black soldier fly larvae (*Hermetia illucens*) improves welfare while maintaining performance of piglets post-weaning. *Sci Rep* 2021;11:1–10. <https://doi.org/10.1038/s41598-021-86765-3>.
- Islam MM, Mun H-S, Bostami A, Yang C-J. Effect of dried mealworm larvae probiotics on quality and oxidative stability of meat in broilers. *J Poult Sci* 2016;4:462–7.
- Jang HA, Park KB, Kim BB, Ali Mohammadie Kojour M, Bae YM, Baliarsingh S, et al. Bacterial but not fungal challenge up-regulates the transcription of Coleoptericin genes in *Tenebrio molitor*. *Entomol Res* 2020a;50:440–9. <https://doi.org/10.1111/1748-5967.12465>.
- Jang HA, Park KB, Kim BB, Ali Mohammadie Kojour M, Bae YM, Baliarsingh S, et al. *In silico* identification and expression analyses of defensin genes in the mealworm beetle *Tenebrio molitor*. *Entomol Res* 2020b;50:575–85. <https://doi.org/10.1111/1748-5967.12468>.
- Janssen RH, Vincken J-P, van den Broek LAM, Fogliano V, Lakemond CMM. Nitrogen-protein conversion factors for three edible insects: *Tenebrio molitor*, *Alphitobius diaperinus*, and *Hermetia illucens*. *J Agric Food Chem* 2017;65:2275–8.
- Jarett JK, Carlson A, Rossoni Serao M, Strickland J, Serfilippi L, Ganz HH. Diets with and without edible cricket support a similar level of diversity in the gut microbiome of dogs. *PeerJ* 2019;7:e7661. <https://doi.org/10.7717/peerj.7661>.
- Jin XH, Heo PS, Hong JS, Kim NJ, Kim YY. Supplementation of dried mealworm (*Tenebrio molitor* larva) on growth performance, nutrient digestibility and blood profiles in weaning pigs. *Asian-Australas J Anim Sci* 2016;29:979.
- Józefiak A, Engberg RM. Insect proteins as a potential source of antimicrobial peptides in livestock production. A review. *J Anim Feed Sci* 2017;26:87–99. <https://doi.org/10.22358/jafs/69998/2017>.
- Józefiak D, Józefiak A, Kierończyk B, Rawski M, Świątkiewicz S, Długosz J, et al. Insects - a natural nutrient source for poultry - a review. *Ann Anim Sci* 2016;16:297–313. <https://doi.org/10.1515/aoas-2016-0010>.
- Józefiak A, Kierończyk B, Rawski M, Mazurkiewicz J, Benzertiha A, Gobbi P, et al. Full-fat insect meals as feed additive – the effect on broiler chicken growth performance and gastrointestinal tract microbiota. *J Anim Feed Sci* 2018;27:131–9. <https://doi.org/10.22358/jafs/91967/2018>.
- Józefiak A, Nogales-Merida S, Mikołajczak Z, Rawski M, Kierończyk B, Mazurkiewicz J. 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* 2019;19:747–65.
- Józefiak A, Benzertiha A, Kierończyk B, Łukomska A, Wesolowska I, Rawski M. Improvement of cecal commensal microbiome following the insect additive into Chicken Diet. *Animals* 2020;10:577. <https://doi.org/10.3390/ani10040577>.
- Jung YH, Park BY, Lee D-K, Hahn Y, Chung JH, Han DM, et al. Biochemical and molecular characterization of an antifungal protein from *Tenebrio molitor* larvae. *Mol Cells* 1995;5:287–92.
- Kamau E, Mutungi C, Kinyuru J, Imathiu S, Tanga C, Affognon H, et al. Effect of packaging material, storage temperature and duration on the quality of semi-processed adult house cricket meal. *J Food Res* 2017;7:21–31.
- Karlsen Ø, Amlund H, Berg A, Olsen RE. The effect of dietary chitin on growth and nutrient digestibility in farmed Atlantic cod, Atlantic salmon and Atlantic halibut. *Aquac Res* 2017;48:123–33.
- Kawasaki K, Osafune T, Tamehira S, Yano K. Piglets can secrete acidic mammalian chitinase from the pre weaning stage. *Sci Rep* 2021;11:1–6. <https://doi.org/10.1038/s41598-020-80368-0>.
- Keshavarz M, Jo YH, Park KB, Ko HJ, Edosa TT, Lee YS, et al. TmDorX2 positively regulates antimicrobial peptides in *Tenebrio molitor* gut, fat body, and hemocytes in response to bacterial and fungal infection. *Sci Rep* 2019;9:16878. <https://doi.org/10.1038/s41598-019-53497-4>.
- Kierończyk B, Rawski M, Józefiak A, Mazurkiewicz J, Świątkiewicz S, Siwek M, et al. Effects of replacing soybean oil with selected insect fats on broilers. *Anim Feed*

- Sci Technol 2018a;240:170–83. <https://doi.org/10.1016/j.anifeeds.2018.04.002>.
- Kierończyk B, Rawski M, Pawełczyk P, Różyńska J, Golusik J, Mikołajczak Z, et al. Do insects smell attractive to dogs? A comparison of dog reactions to insects and commercial feed aromas - a preliminary study. *Ann Anim Sci* 2018b;18:795–800. <https://doi.org/10.2478/aoas-2018-0012>.
- Kierończyk B, Sypniewski J, Rawski M, Czekala W, Świątkiewicz S, Józefiak D. 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* 2020;20:157–77. <https://doi.org/10.2478/aoas-2019-0066>.
- Kierończyk B, Rawski M, Mikołajczak Z, Leciejewska N, Józefiak D. *Hermetia illucens* fat affects the gastrointestinal tract selected microbial populations, their activity, and the immune status of broiler chickens. *Ann Anim Sci* 2021;2:663–75. <https://doi.org/10.2478/aoas-2021-0071>.
- Kilburn LR, Carlson AT, Lewis E, Seroa MCR. Cricket (*Gryllos sigillatus*) meal fed to healthy adult dogs does not affect general health and minimally impacts apparent total tract digestibility. *J Anim Sci* 2020;98:1–8. <https://doi.org/10.1093/jas/skaa083>.
- Kim T-K, Yong HI, Kim Y-B, Kim H-W, Choi Y-S. Edible insects as a protein source: a review of public perception, processing technology, and research trends. *Food Sci Anim Resour* 2019;39:521–40. <https://doi.org/10.5851/ksfa.2019.e53>.
- Kim YB, Kim DH, Jeong SB, Lee JW, Kim TH, Lee HG, et al. Black soldier fly larvae oil as an alternative fat source in broiler nutrition. *Poult Sci* 2020;99:3133–43. <https://doi.org/10.1016/j.psj.2020.01.018>.
- Kim B, Bang HT, Jeong JY, Kim M, Kim KH, Chun JL, et al. Effects of dietary supplementation of black soldier fly (*Hermetia illucens*) larvae oil on broiler health. *J Poult Sci* 2020;200070.
- Kim B, Bang HT, Kim KH, Kim MJ, Jeong JY, Chun JL, et al. Evaluation of black soldier fly larvae oil as a dietary fat source in broiler chicken diets. *J Anim Sci Technol* 2020b;62:187–97. <https://doi.org/10.5187/jast.2020.62.2.187>.
- Ko HS, Kim YH, Kim JS. The produced mealworm meal through organic wastes as a sustainable protein source for weanling pigs. *J Anim Sci Technol* 2020;62:365–73. <https://doi.org/10.5187/JAST.2020.62.3.365>.
- Kozłowski K, Ognik K, Stepińska A, Juśkiewicz J, Zduńczyk Z, Kierończyk B, et al. Growth performance, immune status and intestinal fermentative processes of young turkeys fed diet with additive of full fat meals from *Tenebrio molitor* and *Hermetia illucens*. *Anim Feed Sci Technol* 2021;278:114994. <https://doi.org/10.1016/j.anifeeds.2021.114994>.
- Lalander C, Diener S, Zurbrugg C, Vinnerås B. Effects of feedstock on larval development and process efficiency in waste treatment with black soldier fly (*Hermetia illucens*). *J Clean Prod* 2019;208:211–9.
- Larouche J, Deschamps M-H, Saucier L, Lebeuf Y, Doyen A, Vandenberg GW. Effects of killing methods on lipid oxidation, colour and microbial load of black soldier fly (*Hermetia illucens*) larvae. *Animals* 2019;9:182. <https://doi.org/10.3390/ani9040182>.
- Lasekan OO, Lasekan W, Idowu MA, Ojo OA. Effect of extrusion cooking conditions on the nutritional value, storage stability and sensory characteristics of a maize-based snack food. *J Cereal Sci* 1996;24:79–85.
- Lazzarotto V, Corraze G, Leprevost A, Quillet E, Dupont-Nivet M, Médale F. Three-year breeding cycle of rainbow trout (*Oncorhynchus mykiss*) fed a plant-based diet, totally free of marine resources: consequences for reproduction, fatty acid composition and progeny survival. *PLoS One* 2015;10:e0117609.
- Le Gall M, Behmer ST. Effects of protein and carbohydrate on an insect herbivore: the vista from a fitness landscape. *Integr Comp Biol* 2014;54:942–54.
- Lee D-K, Kim BS, Kim D-H, Kim S, Chung JH, MinHan D, et al. Expression of an insect antifungal protein of *Tenebrio molitor* in *Escherichia coli*. *Mol Cells* 1995;5:429–35.
- Lee YJ, Chung TJ, Park CW, Hahn Y, Chung JH, Lee BL, et al. Structure and expression of the Tenecin 3 gene in *Tenebrio molitor*. *Biochem Biophys Res Commun* 1996;218:6–11. <https://doi.org/10.1006/bbrc.1996.0002>.
- Lee K-S, Yun E-Y, Goo T-W. Antimicrobial activity of an extract of *Hermetia illucens* larvae immunized with *Lactobacillus casei* against *Salmonella* species. *Insects* 2020;11:704. <https://doi.org/10.3390/insects11100704>.
- Lee KI, Chae Y, Yun T, Koo Y, Lee D, Kim H, et al. Clinical application of insect-based diet in canine allergic dermatitis. *Korean J Vet Res* 2021;61:e36. <https://doi.org/10.14405/kjvr.2021.61.e36>.
- Lei XJ, Kim TH, Park JH, Kim IH. Evaluation of supplementation of defatted black soldier fly (*Hermetia illucens*) larvae meal in beagle dogs. *Ann Anim Sci* 2019;19:767–77.
- Leni G, Caligiani A, Sforza S. Killing method affects the browning and the quality of the protein fraction of black soldier fly (*Hermetia illucens*) prepupae: a metabolomics and proteomic insight. *Food Res Int* 2019;115:116–25.
- Li Z, Mao R, Teng D, Hao Y, Chen H, Wang Xiumin, et al. Antibacterial and immunomodulatory activities of insect defensins-DLP2 and DLP4 against multidrug-resistant *Staphylococcus aureus*. *Sci Rep* 2017;7:12124. <https://doi.org/10.1038/s41598-017-10839-4>.
- Lisenko K, de Godoy M, Oliveira M, Silva T, Fontes T, Costa D, et al. PSXIII-26 compositional analysis and effects of dietary supplementation of insect meals on nutrient digestibility and gut health of adult dogs. *J Anim Sci* 2018;96:158–9.
- Liu X, Chen X, Wang H, Yang Q, Rehman K, Li W, et al. Dynamic changes of nutrient composition throughout the entire life cycle of black soldier fly. *PLoS One* 2017;12:1–21. <https://doi.org/10.1371/journal.pone.0182601>.
- Manditsera FA, Luning PA, Fogliano V, Lakemond CMM. Effect of domestic cooking methods on protein digestibility and mineral bioaccessibility of wild harvested adult edible insects. *Food Res Int* 2019;121:404–11.
- Marono S, Piccolo G, Loponte R, Di Meo C, Attia YA, Nizza A, et al. *In vitro* crude protein digestibility of *Tenebrio molitor* and *Hermetia illucens* insect meals and its correlation with chemical composition traits. *Ital J Anim Sci* 2015;14:338–43. <https://doi.org/10.4081/ijas.2015.3889>.
- Melenchón F, Larrán AM, de Mercado E, Hidalgo MC, Cardenete G, Barroso FG, et al. Potential use of black soldier fly (*Hermetia illucens*) and mealworm (*Tenebrio molitor*) insectmeals in diets for rainbow trout (*Oncorhynchus mykiss*). *Aquac Nutr* 2021;27:491–505.
- Meneguz M, Schiavone A, Gai F, Dama A, Lussiana C, Renna M, et al. Effect of rearing substrate on growth performance, waste reduction efficiency and chemical composition of black soldier fly (*Hermetia illucens*) larvae. *J Sci Food Agric* 2018;98:5776–84.
- Meyer S, Gessner DK, Braune MS, Friedhoff T, Most E, Höring M, et al. Comprehensive evaluation of the metabolic effects of insect meal from *Tenebrio molitor* L. in growing pigs by transcriptomics, metabolomics and lipidomics. *J Anim Sci Biotechnol* 2020;11:1–19.
- Mikołajczak Z, Rawski M, Mazurkiewicz J, Kierończyk B, Józefiak D. The effect of hydrolyzed insect meals in sea trout fingerling (*Salmo trutta* p. trutta) diets on growth performance, microbiota and biochemical blood parameters. *Animals* 2020;10:1031. <https://doi.org/10.3390/ani10061031>.
- Moon HJ, Lee SY, Kurata S, Natori S, Lee BL. Purification and molecular cloning of cDNA for an inducible antibacterial protein from larvae of the Coleopteran, *Tenebrio molitor*. *J Biochem* 1994;116:53–8. <https://doi.org/10.1093/oxfordjournals.jbchem.a124502>.
- Neumann C, Velten S, Liebert F. N balance studies emphasize the superior protein quality of pig diets at high inclusion level of algae meal (*Spirulina platensis*) or insect meal (*Hermetia illucens*) when adequate amino acid supplementation is ensured. *Animals* 2018;8:1–14. <https://doi.org/10.3390/ani8100172>.
- Nyangena DN, Mutungi C, Imathiu S, Kinyuru J, Affognon H, Ekese S, et al. Effects of traditional processing techniques on the nutritional and microbiological quality of four edible insect species used for food and feed in east Africa. *Foods* 2020;9:574. <https://doi.org/10.3390/foods9050574>.
- Okin GS. Environmental impacts of food consumption by dogs and cats. *PLoS One* 2017;12:e0181301.
- Olsen RL, Hasan MR. A limited supply of fishmeal: impact on future increases in global aquaculture production. *Trends Food Sci Technol* 2012;27:120–8.
- Oonincx DGAB, Laurent S, Veenbos ME, van Loon JJA. Dietary enrichment of edible insects with omega 3 fatty acids. *Insect Sci* 2020;27:500–9.
- Park S-I, Yoe SM. A novel cecropin-like peptide from black soldier fly, *Hermetia illucens*: isolation, structural and functional characterization. *Entomol Res* 2017a;47:115–24. <https://doi.org/10.1111/1748-5967.12226>.
- Park S-I, Yoe SM. Defensin-like peptide3 from black soldier fly: identification, characterization, and key amino acids for anti-Gram-negative bacteria. *Entomol Res* 2017b;47:41–7. <https://doi.org/10.1111/1748-5967.12214>.
- Park S-I, Chang BS, Yoe SM. Detection of antimicrobial substances from larvae of the black soldier fly, *Hermetia illucens* (Diptera: Stratiomyidae). *Entomol Res* 2014;44:58–64. <https://doi.org/10.1111/1748-5967.12050>.
- PaBlack N, Zentek J. Acceptance, tolerance and apparent nutrient digestibility of complete diets based on larvae meal of *Hermetia illucens* in cats. *Tierarztl Prax K H* 2018;46:213–21.
- Pérez-Calvo E, Castrillo C, Baucells MD, Guada JA. Effect of rendering on protein and fat quality of animal by-products. *J Anim Physiol Anim Nutr* 2010;94:e154–63.
- Poelaert C, Beckers Y, Despret X, Portetelle D, Francis F, Bindelle J. *In vitro* evaluation of fermentation characteristics of two types of insects as potential novel protein feeds for pigs. *J Anim Sci* 2016;94:198–201.
- Prélaud P. Allergologie canine. 2nd ed. Paris: Masson; 1999.
- Ramos-Elorduy J. Energy supplied by edible insects from Mexico and their nutritional and ecological importance. *Ecol Food Nutr* 2008;47:280–97. <https://doi.org/10.1080/03670240701805074>.
- Raubenheimer D, Simpson SJ. Nutrient balancing in grasshoppers: behavioural and physiological correlates of dietary breadth. *J Exp Biol* 2003;206:1669–81.
- Ravi HK, Vian MA, Tao Y, Degrou A, Costil J, Trespeuch C, et al. Alternative solvents for lipid extraction and their effect on protein quality in black soldier fly (*Hermetia illucens*) larvae. *J Clean Prod* 2019;238:117861.
- Ravi HK, Degrou A, Costil J, Trespeuch C, Chemat F, Vian MA. Effect of devitalization techniques on the lipid, protein, antioxidant, and chitin fractions of black soldier fly (*Hermetia illucens*) larvae. *Eur Food Res Technol* 2020;246:2549–68.
- Rehman K, Rehman RU, Somroo AA, Cai M, Zheng L, Xiao X, et al. Enhanced bioconversion of dairy and chicken manure by the interaction of exogenous bacteria and black soldier fly larvae. *J Environ Manage* 2019;237:75–83.
- Renna M, Schiavone A, Gai F, Dabbou S, Lussiana C, Malfatto V, et al. Evaluation of the suitability of a partially defatted black soldier fly (*Hermetia illucens* L.) larvae meal as ingredient for rainbow trout (*Oncorhynchus mykiss* Walbaum) diets. *J Anim Sci Biotechnol* 2017;8:1–13.
- Roeder KA, Behmer ST. Lifetime consequences of food protein-carbohydrate content for an insect herbivore. *Funct Ecol* 2014;28:1135–43.
- Roh K-B, Kim C-H, Lee H, Kwon H-M, Park J-W, Ryu J-H, et al. Proteolytic cascade for the activation of the insect Toll pathway induced by the fungal cell wall component. *J Biol Chem* 2009;284:19474–81. <https://doi.org/10.1074/jbc.M109.007419>.
- Russo N, Pagani E, Schiavone A, Gasco L, Nevy J, Silvia M, et al. *In vivo* and *in vitro* digestibility of extruded dog foods with *Hermetia illucens*. *Ital J Anim Sci* 2019;18:s1.
- Schiavone A, Dezzutto D, Bergagna S, Gai F, De Marco M, Meneguz M, et al. 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* 2016;16:93–100. <https://doi.org/10.1080/1828051x.2016.1249968>.
- Schiavone A, Dabbou S, De Marco M, Cullere M, Biasato I, Biasibetti E, et al. Black soldier fly larva fat inclusion in finisher broiler chicken diet as an alternative fat source. *Animal* 2018;1–8. <https://doi.org/10.1017/S1751731117003743>.
- Schley L, Roper TJ. Diet of wild boar *Sus scrofa* in Western Europe, with particular reference to consumption of agricultural crops. *Mamm Rev* 2003;33:43–56. <https://doi.org/10.1046/j.1365-2907.2003.00010.x>.
- Shin HS, Park S-I. Novel attacin from *Hermetia illucens*: cDNA cloning, characterization, and antibacterial properties. *Prep Biochem Biotechnol* 2019;49:279–85. <https://doi.org/10.1080/10826068.2018.1541807>.
- Simpson SJ, Simmonds MSJ, Blaney WM. A comparison of dietary selection behaviour in larval *Locusta migratoria* and *Spodoptera littoralis*. *Physiol Entomol* 1988;13:225–38.
- Sprangers T, Michiels J, Vrancx J, Ovyne A, Eeckhout M, De Clercq P, et al. Gut antimicrobial effects and nutritional value of black soldier fly (*Hermetia illucens* L.) prepupae for weaned piglets. *Anim Feed Sci Technol* 2018;235:33–42.
- Sprangers T, Schillewaert S, Wouters F. Optimizing nutrition of black soldier fly larvae. In: 70th Annu. Meet. Eur. Fed. Anim. Sci. (EAAP); 2019. Locat. Ghent (Abstract).
- Stadtlander T, Stamer A, Buser A, Wohlfahrt J, Leiber F, Sandrock C. *Hermetia illucens* meal as fish meal replacement for rainbow trout on farm. *J Insects as Food Feed* 2017;3:165–75.
- Sultana A, Luo H, Ramakrishna S. Harvesting of antimicrobial peptides from insect (*Hermetia illucens*) and its applications in the food packaging. *Appl Sci* 2021;11. <https://doi.org/10.3390/app11156991>.
- Sypniewski J, Kierończyk B, Benzertih A, Mikolajczak Z, Pruszyńska-Oszmałek E, Kotodziejski P, et al. Replacement of soybean oil by *Hermetia illucens* fat in Turkey nutrition: effect on performance, digestibility, microbial community, immune and physiological status and final product quality. *Br Poult Sci* 2020;1–9.
- Tabata E, Kashimura A, Kikuchi A, Masuda H, Miyahara R, Hiruma Y, et al. Chitin digestibility is dependent on feeding behaviors, which determine acidic chitinase mRNA levels in mammalian and poultry stomachs. *Sci Rep* 2018;8:1–11. <https://doi.org/10.1038/s41598-018-19940-8>.
- Terova G, Rimoldi S, Ascione C, Gini E, Ceccotti C, Gasco L. Rainbow trout (*Oncorhynchus mykiss*) gut microbiota is modulated by insect meal from *Hermetia illucens* prepupae in the diet. *Rev Fish Biol Fish* 2019;29:465–86.
- Timbermont L, Lanckriet A, Dewulf J, Nollet N, Schwarzer K, Haesebrouck F, et al. Control of *Clostridium perfringens*-induced necrotic enteritis in broilers by target-released butyric acid, fatty acids and essential oils. *Avian Pathol* 2010;39:117–21.
- Tiralla N, Holzapfel M, Ansoorge H. Feeding ecology of the wolf (*Canis lupus*) in a near-natural ecosystem in Mongolia. *Mamm Biol* 2021;101:83–9. <https://doi.org/10.1007/s42991-020-00093-z>.
- Tschirner M, Simon A. Influence of different growing substrates and processing on the nutrient composition of black soldier fly larvae destined for animal feed. *J Insects as Food Feed* 2015;1:249–59. <https://doi.org/10.3920/JIFF2014.0008>.
- van Zanten HHE, Bikker P, Meerburg BG, de Boer IJM. Attributional versus consequential life cycle assessment and feed optimization: alternative protein sources in pig diets. *Int J Life Cycle Assess* 2018;23:1–11. <https://doi.org/10.1007/s11367-017-1299-6>.
- Vianna GMS, Zeller D, Pauly D. Fisheries and policy implications for human nutrition. *Curr Environ Health Reports* 2020;1–9.
- Wacyk J, Powell M, Rodnick K, Overturf K, Hill RA, Hardy R. Dietary protein source significantly alters growth performance, plasma variables and hepatic gene expression in rainbow trout (*Oncorhynchus mykiss*) fed amino acid balanced diets. *Aquaculture* 2012;356:223–34.
- Wade B, Keyburn A. The true cost of necrotic enteritis. *World Poult* 2015;31:16–7.
- Waldbauer GP, Bhattacharya AK. Self-selection of an optimum diet from a mixture of wheat fractions by the larvae of *Tribolium confusum*. *J Insect Physiol* 1973;19:407–18.
- Wang S, Zeng X, Yang Q, Qiao S. Antimicrobial peptides as potential alternatives to antibiotics in food animal industry. *Int J Mol Sci* 2016;17:603. <https://doi.org/10.3390/ijms17050603>.
- Wen L-F, He J-G. Dose-response effects of an antimicrobial peptide, a cecropin hybrid, on growth performance, nutrient utilisation, bacterial counts in the digesta and intestinal morphology in broilers. *Br J Nutr* 2012;108:1756–63. <https://doi.org/10.1017/S0007114511007240>.
- Weththasinghe P, Hansen JØ, Nøklund D, Lagos L, Rawski M, Øverland M. Full-fat black soldier fly larvae (*Hermetia illucens*) meal and paste in extruded diets for Atlantic salmon (*Salmo salar*): effect on physical pellet quality, nutrient digestibility, nutrient utilization and growth performances. *Aquaculture* 2021;530:735785. <https://doi.org/10.1016/j.aquaculture.2020.735785>.
- Woolley L-A, Murphy BP, Geyle HM, Legge SM, Palmer RA, Dickman CR, et al. Introduced cats eating a continental fauna: invertebrate consumption by feral cats (*Felis catus*) in Australia. *Wildl Res* 2020;47:610–23.
- Xia J, Ge C, Yao H. Antimicrobial peptides from black soldier fly (*Hermetia illucens*) as potential antimicrobial factors representing an alternative to antibiotics in livestock farming. *Animals* 2021;11:1937. <https://doi.org/10.3390/ani11071937>.
- Xiong X, Yang HS, Li L, Wang YF, Huang RL, Li FN, et al. Effects of antimicrobial peptides in nursery diets on growth performance of pigs reared on five different farms. *Livest Sci* 2014;167:206–10. <https://doi.org/10.1016/j.livsci.2014.04.024>.
- Yi H-Y, Chowdhury M, Huang Y-D, Yu X-Q. Insect antimicrobial peptides and their applications. *Appl Microbiol Biotechnol* 2014;98:5807–22.
- Yoon JH, Ingale SL, Kim JS, Kim KH, Lee SH, Park YK, et al. Effects of dietary supplementation of antimicrobial peptide-A3 on growth performance, nutrient digestibility, intestinal and fecal microflora and intestinal morphology in weanling pigs. *Anim Feed Sci Technol* 2012;177:98–107. <https://doi.org/10.1016/j.anifeedsci.2012.06.009>.
- Yoon JH, Ingale SL, Kim JS, Kim KH, Lohakare J, Park YK, et al. Effects of dietary supplementation with antimicrobial peptide-P5 on growth performance, apparent total tract digestibility, faecal and intestinal microflora and intestinal morphology of weanling pigs. *J Sci Food Agric* 2013;93:587–92. <https://doi.org/10.1002/jsfa.5840>.
- Yoon JH, Ingale SL, Kim JS, Kim KH, Lee SH, Park YK, et al. Effects of dietary supplementation of synthetic antimicrobial peptide-A3 and P5 on growth performance, apparent total tract digestibility of nutrients, fecal and intestinal microflora and intestinal morphology in weanling pigs. *Livest Sci* 2014;159:53–60. <https://doi.org/10.1016/j.livsci.2013.10.025>.
- Yu M, Li Z, Chen W, Rong T, Wang G, Li J, et al. Use of *Hermetia illucens* larvae as a dietary protein source: effects on growth performance, carcass traits, and meat quality in finishing pigs. *Meat Sci* 2019a;158:107837. <https://doi.org/10.1016/j.meatsci.2019.05.008>.
- Yu M, Li Z, Chen W, Rong T, Wang G, Ma X. *Hermetia illucens* larvae as a potential dietary protein source altered the microbiota and modulated mucosal immune status in the colon of finishing pigs. *J Anim Sci Biotechnol* 2019b;10:50.
- Yu M, Li Z, Chen W, Rong T, Wang G, Wang F, et al. Evaluation of full-fat *Hermetia illucens* larvae meal as a fishmeal replacement for weanling piglets: effects on the growth performance, apparent nutrient digestibility, blood parameters and gut morphology. *Anim Feed Sci Technol* 2020a;264:114431. <https://doi.org/10.1016/j.anifeedsci.2020.114431>.
- Yu M, Li Z, Chen W, Wang G, Rong T, Liu Z, et al. *Hermetia illucens* larvae as a fishmeal replacement alters intestinal specific bacterial populations and immune homeostasis in weanling piglets. *J Anim Sci* 2020b;98:1–13. <https://doi.org/10.1093/JAS/SKZ395>.
- Zeitl JO, Fennhoff J, Kluge H, Stangl GI, Eder K. Effects of dietary fats rich in lauric and myristic acid on performance, intestinal morphology, gut microbes, and meat quality in broilers. *Poult Sci* 2015;94:2404–13.
- Zhineng Y, Ying M, Bingjie T, Rouxian Z, Qiang Z. Intestinal microbiota and functional characteristics of black soldier fly larvae (*Hermetia illucens*). *Ann Microbiol* 2021;71:13. <https://doi.org/10.1186/s13213-021-01626-8>.