



INSECT FAT IN ANIMAL NUTRITION – A REVIEW*

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Abstract

The aim of this review is to discuss the usage of insect fats as an energy source in animal nutrition. Insects are a rich carrier of proteins, fat, and minerals. They are successfully introduced in animal diets (poultry, swine, rabbits, fish, and pets) as a source of many nutrients, including energy and essential fatty acids (FAs). The insects' fat content and quality are highly affected by the type of substrate provided to the insects during the rearing period. The majority of the studies have shown that insect fats may be used as promising substitutes for conventional energy resources in animal nutrition without adverse effects on growth performance and feed utilization. They can positively affect meat quality by increasing the level of long-chain polyunsaturated FAs but may also positively influence animals by regulating the gut microbiota and stimulating the immune system. In conclusion, insect fat supplementation showed promising results in terms of their application in animal nutrition. However, compared to insect protein application, very few studies have been performed on insect fats. Therefore, because of the fat quality and content of insects, there is a need to extend experimentation regarding their implementation in animals' diets as a replacement for conventional dietary energy resources.

Key words: insects, rearing substrate, fatty acids, nutritive value, alternative dietary fat, soybean and fish oils replacement

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Fats and oils are supplemented in livestock diets to increase the dietary energy level to meet the daily nutrient requirements and are considered an essential nutrient for all animal species (Ravindran et al., 2016). Currently, several fat and oil sources are applied in livestock nutrition, i.e., rendering byproducts, vegetable oils, byproducts of oil refining, and recovered frying oils (Ravindran et al., 2016). According to a report published by the United States Department of Agriculture (USDA, 2018), soybean oil is the most produced oil worldwide, followed by palm oil. Furthermore, feed for animals is one of the major contributors to land use, greenhouse gas emissions and water demand and threats to biodiversity (Mungkung et al., 2013). Van Zanten et al. (2015) reported that conventional feedstuffs, i.e., soybean and palm oils, have a huge negative impact on the environment, especially when they are related to land, water use, greenhouse gas emissions, and biodiversity limitations. Therefore, animal nutritionists will eventually have to face the elimination of raw materials that are less sustainable. Recently, insects have received considerable attention due to their usage in animal nutrition because of their high nutritive values, rapid development and high bioconversion abilities (Pinotti et al., 2019). It is well documented that insects are a perfect source of proteins and different fatty acids but also of various bioactive compounds that may support animal growth by stimulation of their immune response. In the European Union, it is regulated that only seven species can be reared (annex II of Regulation (EU) 2017/893; EC, 2017) including *Hermetia illucens*, *Musca domestica*, *Tenebrio molitor*, *Alphitobius diaperinus*, *Acheta domestica*, *Gryllos sigillatus*, and *Gryllus assimilis*.

Fat is the second-largest component in insects after protein. Insects' fat content varies between 7.9% and 47% on dry matter basis (Barker et al., 1998; Finke, 2015; Meneguz et al., 2018; Nogales-Mérida et al., 2018; Danieli et al., 2019). One issue that can be a challenge to nutritionists during feed formulation is that not all insect species have the same composition of their fatty acids (FAs) profile, and therefore, the nutritive value of the fat. The fat content in insects depends on several factors, such as species, life stage, diet, and environmental conditions (Fontaneto et al., 2011; Oonincx et al., 2015; Barragan-Fonseca et al., 2018; Oonincx et al., 2019). However, the fatty acid profile could also be affected by the abovementioned factors (Barroso et al., 2017); thus, a large variety can be found (Sosa and Fogliano, 2017). Finally, changes in FAs are extremely rapid in insects and occur sometimes only a few hours after exposure to, for instance, a new diet, while in mammals, such changes can take weeks.

Fat extracted from insects has been successfully introduced in animal nutrition as an alternative to conventional resources of energy, i.e., in broiler chickens (Schivavone et al., 2017, 2018; Kierończyk et al., 2018; Benzertiha et al., 2019; Kim et al., 2020), turkeys (Sypniewski et al., 2020), laying hens (Heuel et al., 2019), rabbits (Dalle Zotte et al., 2018; Martins et al., 2018; Gasco et al., 2019 a, b), and many fish species (Li et al., 2016; Belghit et al., 2018). The specificity of insects' rearing and the beneficial effects of insect biomass-based products on livestock animals have resulted in a growing interest in the commercial usage of insects in animal nutrition. However, most of the current available studies about insect biomass application in animal nutrition are focused on the replacement of the conventional protein

resources, while much less attention is paid to fat as an energy resource. Due to the insects' fat content and FA profiles, its application in animal nutrition should be taken into consideration. Therefore, there is a need to systematize the current knowledge, especially in the case of the usage of insect fat. To the best of our knowledge, the current review is the first comprehensive summary of application of insect fat in animal nutrition.

Insect lipids: An overview

Insect fat bodies, similar to fat tissue in vertebrates, are one of the main energy substrate storage locations. However, in insects, this tissue also plays a more comprehensive role because it participates *inter alia* in vitellogenesis, hormonal regulation of life processes, synthesis of antimicrobial peptides and general response to stress factors (Chapman, 1998). According to Bailey (1975) and Canavoso et al. (2001), up to 90% of the insect lipids, which comprise the main fat body component, is principally reserved in the form of triglyceride, and the remainder is stored inside compartments called lipid droplets. These structures play a major role in the regulation of lipolysis by protecting the triglycerides from lipase activity (Arrese and Soulages, 2010). Furthermore, triglycerides are mainly synthesized from dietary carbohydrates, FAs or proteins (Arrese and Soulages, 2010). Fatty acids stored in the lipid droplets are necessary, i.e., to provide energy to the flight muscles in the form of trehalose, proline, or diglyceride; to provide storage materials for the growing oocytes; and to maintain the metabolic activity of other tissues and maintain the needs of the organism during stress responses (Arrese and Soulages, 2010). The second largest component of the lipids of insects is phospholipids, which consist mainly of cell membrane structures (Ekpo et al., 2009). However, the contents of the FAs of the lipids stored depend mainly on species, feeding type and the development stage of the insects (Ziegler, 1997; Lorenz, 2001; Pontes et al., 2008; Adámek et al., 2019; Ewald et al., 2020).

A number of methods have been reported to extract insect fat, including the Soxhlet method and supercritical CO₂ (SC-CO₂) extraction (Tzompa-Sosa et al., 2014; Purschke et al., 2017; Kierończyk et al., 2018; Sypniewski et al., 2020). It has been reported that the extraction method does not have a noticeable impact on the FA profile of the lipids. Purschke et al. (2017) did not observe any differences between the SC-CO₂ and hexane extraction methods regarding the physico-chemical properties and composition of the obtained fats. However, the extraction yield was found to be affected by the method used. For example, the Soxhlet extraction method is based on solvents, which may reduce the extraction yield. According to Purschke et al. (2017), SC-CO₂ is a very effective method in which the extraction yield can reach up to 95% of the full fat extracted. In a study by Purschke et al. (2017), time and pressure interaction had the main effects on *T. molitor* (TM) larvae defatting. The yield of 95% was achieved at 400/250 bar, 105 min, and 45°C. Kierończyk et al. (2020) used SC-CO₂ to extract the fat from *H. illucens* with 300 bar and a temperature of 40°C. Furthermore, Kim et al. (2019) showed that the SC-CO₂ extraction method could be an effective method for the defatting of *H. illucens* (HI) meals subjected to 10–18 mesh crushing at 350 bar for 6 h. A 95% fat extraction yield was achieved.

Table 1. Comparative data of *Hermetia illucens* (Black Soldier Fly) fat content (% of dry matter) and summarized fatty acids profiles (g/100 g of FAs)

Life stage	Type of substrate fed to the insects	Lipid content (% of DM)	SFA	MUFA	PUFA	Total n6	Total n3	n6/n3	References
larvae	brown algae (<i>A. nodosum</i>) (100%)	8.1	52.5	22.2	24.2	21.1	3.0	7.03	Liland et al., 2017
larvae	processed wheat (100%)	33.6	67.9	12.2	19.4	18.3	1.4	13.07	Liland et al., 2017
larvae	laying hen feed (60%), fish meal (40%) (after 0 min of feeding)	15.8	63.6	16.7	18.4	NA	NA	NA	Barroso et al., 2017
larvae	laying hen feed (60%), fish meal (40%) (after 3 hours of feeding)	22.9	58.9	19.5	20.2	NA	NA	NA	Barroso et al., 2017
larvae	laying hen feed (60%), fish meal (40%) (4 days of feeding)	15.8	51.7	26.2	19.7	NA	NA	NA	Barroso et al., 2017
larvae	chicken layer mash (100%)	NA	68.9	17.7	12.6	12.1	0.53	22.9	Cullere et al., 2019 b
larvae	chicken layer mash (50%) and fish offal (50%)	NA	72.0	18.7	6.99	5.42	1.57	3.45	Cullere et al., 2019 b
larvae	wheat bran	6.40	54.9	19.8	17.7	16.4	1.3	12.61	Kieróńczyk et al., 2020
larvae	carrots	17.35	66.2	15.1	12.1	10.5	1.7	6.17	Kieróńczyk et al., 2020
larvae	cabbages	15.99	68.7	16.2	8.0	7.2	0.8	9.00	Kieróńczyk et al., 2020
larvae	potatoes	7.75	63.3	19.2	7.8	6.9	0.9	7.66	Kieróńczyk et al., 2020
larvae	wheat bran (25%), carrots (25%), cabbages (25%), potatoes (25%)	14.00	68.6	14.0	7.7	6.8	0.9	7.55	Kieróńczyk et al., 2020
larvae	fruit waste	40.70	81.88	13.34	4.78	NA	NA	NA	Meneguz et al., 2018
larvae	winery byproduct	32.22	63.01	18.97	18.02	NA	NA	NA	Meneguz et al., 2018
larvae	brewery byproduct (barley brewers' grains wet)	29.87	61.25	12.74	26.01	NA	NA	NA	Meneguz et al., 2018
larvae	celery (43.4%), oranges (28.9%) and peppers (27.7%)	26.28	78.90	12.33	8.77	NA	NA	NA	Meneguz et al., 2018
larvae	vegetable byproducts substrate	17.97	80.28	12.88	6.84	6.05	0.79	8.23	Renna et al., 2017

larvae	brewery byproduct (barley brewers' grains wet)	29.87	61.25	12.74	26.01	NA	NA	NA	NA	Meneguz et al., 2018
larvae	celery (43.4%), oranges (28.9%) and peppers (27.7%)	26.28	78.90	12.33	8.77	NA	NA	NA	NA	Meneguz et al., 2018
larvae	vegetable byproducts substrate	17.97	80.28	12.88	6.84	6.05	0.79	8.23	8.23	Renna et al., 2017
prepupae	layer hen feed (100%)	33.6	77.44	10.01	12.45	11.59	0.86	13.47	13.47	Spranghers et al., 2017
prepupae	biogas digestate (100%)	21.8	64.82	19.08	9.64	8.04	1.60	5.03	5.03	Spranghers et al., 2017
prepupae	vegetable waste (carrots, peas, salsify and celery)	37.1	82.80	9.54	6.95	4.62	2.33	1.98	1.98	Spranghers et al., 2017
prepupae	restaurant waste (potatoes, rice, pasta and vegetables)	38.6	78.29	11.99	9.43	8.0	1.43	5.59	5.59	Spranghers et al., 2017
prepupae	ground corn (50%), dehydrated alfalfa (30%), wheat bran (20%)	33.0	79.58	10.55	9.87	NA	NA	NA	NA	Danieli et al., 2019
prepupae	ground barley (68%), wheat bran (20%), dehydrated alfalfa (12%)	46.9	86.89	8.49	4.62	NA	NA	NA	NA	Danieli et al., 2019
prepupae	wheat middlings (50%), wheat straw (24%), ground barley (16%), dehydrated alfalfa (10%)	31.9	81.05	9.01	9.94	NA	NA	NA	NA	Danieli et al., 2019
prepupae	wheat middlings (55%), ground barley (15%), dehydrated alfalfa (30%)	32.5	81.35	8.87	9.78	NA	NA	NA	NA	Danieli et al., 2019
prepupae	fruits (apple, pear, and orange)	NA	86.0	11.2	2.8	2.3	0.5	4.6	4.6	Jucker et al., 2017
prepupae	vegetables (lettuce, string green beans, and cabbage)	NA	56.5	27.2	16.2	8.3	6.8	1.2	1.2	Jucker et al., 2017
prepupae	mixed of fruits and vegetables	NA	65.0	11.0	24.1	20.4	2.8	7.3	7.3	Jucker et al., 2017
minimum		6.4	51.7	8.49	2.8	2.3	0.5	1.2		
maximum		46.9	86.89	27.2	26.01	21.1	6.8	22.9		
average		25.22	70.08	15.17	12.68	10.24	1.72	8.05		

NA: not analyzed; SFA: saturated fatty acids; MUFA: monounsaturated fatty acids; PUFA: polyunsaturated fatty acids

Table 2. Comparative data of fat content (% of dry matter) and summarized fatty acids profiles of the fat from *T. molitor* (g/100 g of FAs)

Life stage	Type of substrate fed to the insects	Lipid content (% of DM)	SFA	MUFA	PUFA	Total n6	Total n3	n6/n3	References
larvae	wheat flour (50%) and soybean flour (50%)	39.05	33.2	54.65	11.63	NA	NA	NA	Alves et al., 2016
larvae	wheat flour and soybean flour (50%), bocaiuva pulp flour (50%)	40.45	33.72	54.98	11.01	NA	NA	NA	Alves et al., 2016
larvae	oat flakes with addition of vegetables	42.48	35.05	51.45	11.76	11.49	0.79	14.49	Siemianowska et al., 2013
larvae	wheat flour, brewer's yeast, and wheat bran	40.9	33.6	37.7	22.9	NA	NA	204.1	Megido et al., 2018
larvae	wheat flour bread	43.21	29.60	50.01	19.89	NA	NA	35.64	Dreassi et al., 2017
larvae	wheat flour (33.17%), oat flour (33.17%), corn flour (33.17%), beer yeast (0.5%)	34.68	32.06	50.37	17.33	NA	NA	37.05	Dreassi et al., 2017
pupae	wheat flour bread	42.52	29.79	45.62	23.70	NA	NA	32.09	Dreassi et al., 2017
pupae	wheat flour (33.17%), oat flour (33.17%), corn flour (33.17%), beer yeast (0.5%)	39.81	31.61	49.96	17.87	NA	NA	41.09	Dreassi et al., 2017
larvae	wheat bran substrate	23.6	23.19	35.11	41.39	36.71	4.68	7.84	Iaconisi et al., 2017
larvae	mixture of carrots, cabbage, Chinese cabbage, tomatoes, and potatoes	17.0	29.7	38.4	31.8	NA	NA	NA	Adámková et al., 2016
larvae	wheat flour (25%), oat flour (25%), corn flour (25%), chickpea flour (25%) and carrot for moisture	16.76	31.99	48.49	19.26	NA	NA	39.06	Francardi et al., 2017
larvae	linseed (10%), wheat flour (22.5%), oat flour (22.5%), corn flour (22.5%), chickpea flour (22.5%) and carrot for moisture	15.88	26.58	46.77	25.96	NA	NA	6.38	Francardi et al., 2017
larvae	oat flour (50%), wheat flour (50%) and carrot for moisture	15.48	30.94	48.26	20.48	NA	NA	40.53	Francardi et al., 2017
larvae	linseed (10%), oat flour (45%), wheat flour (45%) carrot for moisture	16.01	26.08	44.61	28.66	NA	NA	4.33	Francardi et al., 2017

larvae	organic wheat flour (100%)	40.10	24.85	55.92	19.18	NA	NA	62.94	Ruschioni et al., 2020
larvae	organic wheat middlings (100%)	34.04	26.11	47.30	26.52	NA	NA	25.52	Ruschioni et al., 2020
larvae	organic wheat middlings enriched with 75% organic olive pomace	36.06	20.37	60.56	19.08	NA	NA	39.37	Ruschioni et al., 2020
	minimum	15.48	20.37	35.11	11.01	11.49	0.79	4.33	
	maximum	43.21	35.05	60.56	41.39	36.71	4.68	204.1	
	average	31.65	29.32	48.24	21.67	24.1	2.74	42.17	

NA: not analyzed; SFA: saturated fatty acids; MUFA: monounsaturated fatty acids; PUFA: polyunsaturated fatty acids

Generally, insect lipids are liquid at room temperature; therefore, they are called insect oil, with the exception of *H. illucens* fats, which are solid at room temperature. Insect oil is mainly dominated by unsaturated fatty acids, which may reach up to 60% of total FAs (Sosa and Fogliano, 2017). The most abundant insect unsaturated fatty acids (UFAs) are oleic acid (C18:1 cis 9) and linoleic acid (C18:2 cis 9,12) (Paul et al., 2017; Rumpold and Schlüter, 2013; Sosa and Fogliano, 2017). However, as we mentioned previously, FA content and composition strongly depend on insect species and stage of development (Paul et al., 2017; Smets et al., 2020). Only a few insect lipids are solid at room temperature and are thus called insect fats. According to Sosa and Fogliano (2017), insect lipids are classified based on the fatty acid composition between vegetable oils and animal fats. Moreover, Müller et al. (2017) showed that the lipid composition of *H. illucens* larvae is comparable to palm oil and palm kernel oil and is solid in room temperature.

Generally, insect fats and oils can be associated with livestock health status; for instance, lauric acid (C12:0) in the form monolaurin has inhibitory activities against viruses, bacteria and parasites (Zeitz et al., 2015; Ushakova et al., 2016). Moreover, according to Dayrit et al. (2015), medium-chain fatty acids (MCFA) and mainly lauric acids have a very high absorption efficiency that is transferred to the liver and used as a direct source of energy rather than being stored as fat for both humans and animals. It is also reported that lauric acids among all saturated fatty acids (SFAs) have the highest oxidation level and the lowest contribution to fat accumulation in humans (DeLany et al., 2000; Dayrit et al., 2014, 2015).

Black soldier fly (*H. illucens*, BSF) is one of the most intensively studied insect species for its use in animal nutrition. The fat content and fatty acid profile from the currently available literature are summarized in Table 1. According to Shurson et al. (2015) fat quality is measured based on the degree of saturation, color, saponification value, and level of free fatty acids. The larvae of *H. illucens* can reach up to 45% of lipids content on a dry basis, with an average of 24.51% of DM (Li et al., 2016). Furthermore, SFAs are the most dominant fatty acids, with an average of 70.08 mg/100 g of FAs (min. 51.7 mg/100 g of FAs, and max. 86.89 mg/100 g of FAs), followed by monounsaturated fatty acids (MUFA) (15.17 mg/100 g of FAs) and polyunsaturated fatty acids (PUFA) (12.68 mg/100 g of FAs). It should be highlighted that lauric acids showed the highest level (Figure 1) (42.41 mg/100 g of FAs) of SFAs, i.e., palmitic (13.68 mg/100 g of FAs), myristic (11.04 mg/100 g of FAs), and stearic (2.02 mg/100 g of FAs), and UFAs, i.e., linoleic (16.15 mg/100 g of FAs) and oleic (13.95 mg/100 g of FAs). However, the nutrients profile of the *H. illucens* varied during different stages of the life cycle (it increased from 4.8% of DM on the first day of larval age to 28.4% of DM on the 14th day of age) and was also influenced by the rearing substrate (Liu et al., 2017; Smets et al., 2020).

Another insect species with potential application in animal nutrition is the larvae of the mealworm beetle (*T. molitor*). From the summarized findings shown in Table 2, *T. molitor* larvae showed an average fat content of 31.65% of DM; the lowest value was 15.48% of DM, while the highest was 43.21% of DM. The fatty acids profile was dominated by MUFAs at a mean level of 48.24 mg/100 g of FAs, with the values ranging between 60.56 and 35.11 mg/100 g of FAs, followed by SFAs

(29.32 mg/100 g of FAs) and PUFAs (21.67 mg/100 g of FAs). It can be concluded that *T. molitor* fat has more UFAs than SFAs, which makes it better than *H. illucens* fat and suitable to be applied in animal nutrition as a source of energy. However, *T. molitor* lipids are characterized by a very high omega 6 to omega 3 fatty acids ratio of 42.17 compared to *H. illucens* fat (8.05). The omega 6 to omega 3 fatty acids ratio is one of the well-known factors to assess healthy diets. The n6/n3 ratio in *T. molitor* lipids was reported to be very high due to the low levels of the n3 fatty acids (Ravzanaadii et al., 2012; Tzompa-Sosa et al., 2014; Paul et al., 2017; Benzertihá et al., 2019 a). It is reported that the addition of omega 3 fatty acids to the feeding substrates will reflect in an increase of these fatty acids in the lipids of *T. molitor* (Dreassi, 2017; Francardi et al., 2017; Ruschioni et al., 2020). Therefore, the higher level of the n6/n3 ratio could be decreased after adjusting the substrate.

Based on the lipid composition, *Bombyx mori* fat could also be used as an alternative dietary fat supplement in animal nutrition. This is related to the fact that *B. mori* showed a very high quality of lipids that was dominated by UFAs. Noteworthy are the high contents of, for example, oleic acid (C18:1), palmitic acids (C16:0) and linolenic acids (Pereira et al., 2003; Tomotake et al., 2010). However, the composition of FAs highly depends on *B. mori* diet. A general comparison between the composition of insect FAs and oils and fats used in animal nutrition is summarized in Figure 1.

A great advantage of using insects in animal nutrition is that the insects' diet modulation and nutrient content may enhance the lipids profile of insects to be more suitable for different livestock species. This relationship has been confirmed for *H. illucens*, *B. mori* and partially for *T. molitor*. For example, feeding fish offal to *H. illucens* can increase the fat content up to 30% and the omega 3 fatty acids up to 3% within 24 hours after supplementation (St-Hilaire et al., 2007). In addition, Kierończyk et al. (2020) demonstrated that the type of rearing substrate affects the crude protein and crude fat of the larvae of *H. illucens*. The larvae fed on wheat bran had a higher level of crude protein and a lower level of crude fat compared to those fed on carrot and cabbage. It should be emphasized that substrates containing a high level of crude fiber may limit the nutrition of the larvae and cause the utilization of the stored lipids in the fat body for their development needs (Tschirner and Simon, 2015). Kierończyk et al. (2020) reported that feeding *H. illucens* larvae different substrates had a noticeable effect on the fatty acid profile of the final product (*H. illucens* fat). For instance, in the study, the authors observed that lauric acid showed profiles of 26%, 33.9%, 37.9%, 41.1%, and 42.1% after feeding the larvae wheat bran, potato, carrot, cabbage, and a mixture of all, respectively. Oonincx et al. (2019) conducted an experiment on *H. illucens* larvae with four dietary treatments of 0%, 1%, 2%, and 4% addition of flaxseed oil, which is a well-known source of omega 3 fatty acids, to the substrate and found that the amount of SFAs was significantly decreased while the amounts of MUFAs and PUFAs significantly increased in treatments with flaxseed oils compared to those without. Liland et al. (2017) modulated the nutrients profile of *H. illucens* larvae after feeding seaweed-enriched media using brown algae (*Ascophyllum nodosum*). The experiment was designed to assess the possibility of taking the nutrients from the feeding medium by the *H. illucens*

larvae. The authors reported that *H. illucens* larvae fed a processed wheat-based diet showed a higher lipid content of 33% of dry matter (DM), while a decrease to 7.7% of DM of lipid content was observed in the case of a brown algae-based diet. Furthermore, the authors showed that the FA profile of the larvae fed a wheat-based diet was five times higher than those fed an algae-based diet (33.2 and 5.7 g per 100 g dried larvae, respectively) and FA profile of both treatments was dominated by SFAs, at 67.9 vs 52.5% (wheat-based, algae-based diets, respectively). It is recommended by the same authors that algae-based diets would increase the 20:5n3 eicosapentaenoic acid (EPA) level in the *H. illucens* larval fats. Spranghers et al. (2017) stated that the highest amount of SFAs in *H. illucens* prepupae was recorded in groups fed with vegetable wastes (i.e., a mixture of carrots, peas, salsify and celery), while the lowest was recorded in groups fed with biogas digestate. It is shown that 30 minutes to 3 hours after feeding, the *H. illucens* larvae could have enough time to have a change in the FA profile of the lipids (Barroso et al., 2017). The same authors reported that the short-term feeding of *H. illucens* larvae could be enough to enrich fats with long-chain fatty acids. Danieli et al. (2019) stated that the FA profile of the *H. illucens* prepupae was significantly affected by the diet that the larvae were fed. Further, SFAs were highest in a treatment rich with nonfiber carbohydrate (86.89 g/100 g of FAs) than other (control group (79.58 g/100 g of FAs), a diet rich with fiber content (81.05 g/100 g of FAs), and a diet rich with protein (81.35 ± 0.35 g of FAs). The addition of vegetables or algae influenced the lipid composition in *H. illucens*. Research by Jucker et al. (2017) showed that a fruit-based diet increased SFAs and decreased PUFA levels compared to other treatments (vegetables, and mixture of fruits and vegetables).

The composition of FAs also strongly depends on the rearing substrate in the case of *B. mori*. Chieco et al. (2019) aimed to evaluate the effect of the strain and the rearing substrate on the nutrient profile of the pupae of *B. mori*. Golden Yellow Nistari and White Polyhybrid were used and fed two different substrates, i.e., fresh mulberry leaves (*Morus alba* L.) and a commercial artificial diet. The authors reported that the feeding substrate significantly affected the crude fat contents of the pupae of both strains. A mulberry leaves-based diet significantly increased the fat content of both strains, i.e., Golden Yellow Nistari (30.7% of DM) and White Polyhybrid (33.3% of DM), while the pupae fed artificial diet showed a lower fat content, i.e., Golden Yellow Nistari (25.1% of DM) and White Polyhybrid (23.3% of DM). The FA profile of the silkworm pupae had higher UFAs than SFAs. The White Polyhybrid strains fed with artificial diets showed the highest level of SF compared to the same strain fed mulberry leaves-based diet and Golden Yellow Nistari fed both diets. Moreover, oleic acid (C18:1) was the most dominant fatty acid, followed by palmitic acid (C16:0) in both strains fed both diets.

Interestingly, some findings (Table 2) showed different levels of fatty acids in *T. molitor* after feeding the same substrate to the larvae, clearly indicating that FAs vary with individual species and could be related to factors other than substrates (Paul et al., 2017; Adámek et al., 2019; Ewald et al., 2020). The fat content and the fatty acids profile of the extracted oil from *T. molitor* larvae fed two different diets (50% wheat flour and 50% soybean flour; 50% wheat flour and soybean flour and 50% bocaiuva pulp flour) did not show any differences. Dreassi et al. (2017) fed *T. molitor* larvae 6 different substrates that varied in the fat content level, from 0.46% to 9.34% of

DM content. The authors noted that the total fat contents of *T. molitor* larvae and pupae were not affected by the dietary treatments. However, the PUFA level of the fat obtained from *T. molitor* larvae was higher in the group fed a diet rich in fat than a diet low in fat content. Francardi et al. (2017) conducted an experiment in which four different dietary treatments were used and enriched with 10% linseed flour, and the authors observed that substrates enriched with linseed showed more fat than without. These changes in the fat content of the substrate did not have any effect on the fat levels of *T. molitor* larvae, which showed the same dominant fatty acids. However, in the same study, *T. molitor* larvae fed diets enriched with linseed showed lower levels of SFAs and MUFAs, while PUFAs were significantly increased in groups supplemented with linseed. Furthermore, linseed addition to the substrate of *T. molitor* significantly decreased the *n6/n3* ratio. The enrichment of *T. molitor* substrate (organic wheat middlings) with 75% organic olive pomace did not significantly increase the fat level of *T. molitor* larvae. However, the enrichment with olive pomace significantly decreased SFAs and PUFAs and increased the levels of MUFAs and *n6/n3* (Ruschioni et al., 2020).

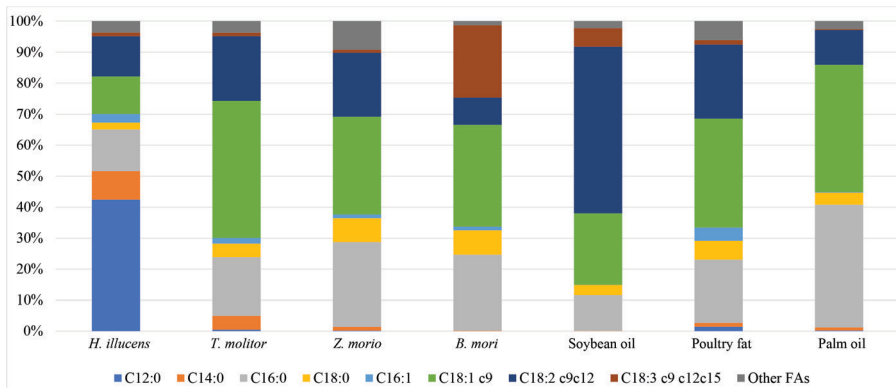


Figure 1. Fatty acid profiles of insect lipids and commonly used fats and oils (% of total FAs) (Finke, 2002; Pereira et al., 2003; Tomotake et al., 2010; Mentang et al., 2011; Ooninx et al., 2012; Siemianowska et al., 2013; Barroso et al., 2014; Alves et al., 2016; Li et al., 2016; Adámková et al., 2016; 2017; Dreassi et al., 2017; Francardi et al., 2017; Iaconisi et al., 2017; Schiavone et al., 2017; Dalle Zotte et al., 2018; Megido et al., 2018; Turek et al., 2018; Alifian et al., 2019; Benzertih et al., 2019; Chieco et al., 2019; Cullere et al., 2019 a; Gasco et al., 2019 a; Mlcek et al., 2019; Kierończyk et al., 2018; 2020; Kim et al., 2020; Ruschioni et al., 2020)

Insect fat in animal nutrition

Poultry

As mentioned previously, insect lipids are rich in linoleic acid (LA) and C18:3 cis9,12,15 alpha-linolenic acid (LNA), with levels comparable to those in some vegetable oils (Sosa and Fogliano, 2017). Several studies have already evaluated the supplementation of insect oils in broiler chicken, turkey, and Japanese quail diets, demonstrating total or partial replacement of commonly used fat and oil sources (Cullere et al., 2016, 2017; Schiavone et al., 2017; Kierończyk et al., 2018, Schia-

vone et al., 2018; Benzertiha et al., 2019; Kierończyk et al., 2020; Kim et al., 2020; Sypniewski et al., 2020). Moreover, the studies available in the literature do not show any adverse effects on the birds' growth performance and/or the final product quality.

Growth performance

The effects of insect lipids on the growth performance parameters in poultry are summarized in Table 3. In the available literature, several trials were carried out, mostly on *H. illucens* and *T. molitor* lipids as substitutes of the conventional fat sources in poultry nutrition. The most recent study was conducted by Kim et al. (2020), who investigated the total replacement of corn oil and coconut oil by *H. illucens* fat in broiler chicken nutrition. The study showed that dietary treatments did not have any effects on the growth performance parameters, i.e., feed intake (FI) and body weight gain (BWG), while the feed conversion ratio (FCR) was significantly reduced in the treatment supplemented with *H. illucens* fat and coconut oil during the entire experimental period (30 days). In the same study, *Clostridium perfringens* counts in ileal and cecal digesta were not affected by any of the dietary treatments. At 15 days of age, *H. illucens* fat increased the levels of acetate, butyrate, valerate, and short-chain fatty acids in the ileal content compared with coconut and corn oil treatments. Furthermore, studies were conducted on broiler chicken to completely or partially replace soybean oil with *H. illucens* fat, and none of the studies showed any negative effects on the growth performance parameters (Schiavone et al., 2017, 2018; Kierończyk et al., 2020; Sypniewski et al., 2020). In a recently conducted study in our research group (Benzertiha et al., 2019), we demonstrated that total replacement of palm oil and poultry fat by *T. molitor* oil did not have any negative effects on the growth performance traits for the whole period of the trial (7 to 30 d). This was also confirmed by Kierończyk et al. (2018) in two independent experiments on broiler chicken, showing a possibility of total or partial replacement of soybean oil by *T. molitor* or *Z. morio* (ZM) oils. Based on the abovementioned studies, it is emphasized that insect fat obtained from *H. illucens*, *T. molitor* and *Z. morio* larvae can replace conventional fat sources in broiler chicken and turkey nutrition without any adverse effect on the growth performance traits. In addition, laying hens fed fat from *H. illucens* larvae did not show any effects on laying performance, body weight (BW) and the FI (Heuel et al., 2019). Recently, Sypniewski et al. (2020) studied the possibility of a total or partial replacement of soybean oil by *H. illucens* fat in young turkeys. During each period of the study, the authors did not find any effects of the dietary treatments on the growth performance parameters, i.e., BWG, FI, and FCR. In addition, the results concern the addition of full-fat meal based on insect biomass, which can partially indicate some biological effects related to usages of insect fats in animal nutrition. Investigation of the substitution of soybean meal and oil or fish meal by *H. illucens* larvae full-fat meal in broiler and laying quail diets did not show any effects on the feed performances, growth performance traits, apparent nutrient digestibility and microbiological composition of excreta (Cullere et al., 2016, 2017; Dalle Zotte et al., 2019). In the authors' studies, in the first dietary treatments, the addition of 10% *H. illucens* full-fat meal replaced 28.4% of soybean oil, and in the second treatment, 15% *H. illucens* full-fat meal was added to replace 100% of soybean oil.

Table 3. Insect fat inclusion in the poultry diets and effects on growth performance traits in comparison with other fat sources used in different trials

Avian species	Insect fat source	Ingredients compared with	Level of inclusion (%)	Experiment period	Effect on the growth performance parameters	References
Broiler chicken	HI fat	Coconut oil and corn oil	Total replacement of fat source (100%)	1 d to 30 d of age	No effects on the BWG and FI; Decreased FCR compared to corn oil	Kim et al., 2020
Broiler chicken	HI fat	Soybean oil	Partial or total replacement (25%, 50%, 75%, and 100%)	1 d to 35 d of age	No effects on the BWG, FI and FCR for the whole period of the trial (1–35 d); FI and FCR were reduced in groups fed HI fat (1–14 d) compared to soybean oil.	Kierończyk et al., 2020
Broiler chicken	HI fat	Soybean oil	Partial or total replacement (50% and 100%)	1 d to 35 d of age	No effects on the BWG, FI and FCR for the whole period of the trial (1–35 d).	Schiavone et al., 2017
Broiler chicken	HI fat	Soybean oil	Partial or total replacement (50% and 100%)	21 d to 48 d of age	No effects on the BWG, FI and FCR for the whole period of the trial (21–48 d).	Schiavone et al., 2018
Broiler chicken	TM oil	Palm oil and poultry fat	Total replacement of fat source (100%)	7 d to 30 d of age	No effects on the BWG, FI and FCR for the whole period of the trial (7–30 d).	Benzertiha et al., 2019
Broiler chicken	TM oil, and ZM oil	Soybean oil	Total replacement of fat source (100%)	1 d to 35 d of age	Exp 1. No effects on the BWG, FI and FCR for the whole period of the trial (1–28 d) Exp 2. No effects on the BWG, FI and FCR for the whole period of the trial (1–28 d)	Kierończyk et al., 2018
Turkey	HI fat	Soybean oil	Partial or total replacement (50% and 100%)	7 d to 28 d of age	No influence on the BWG, FI and FCR	Sypniewski et al., 2020
Broiler quails	HI full-fat meal	Soybean oil	Partial or total replacement of soybean oil (28.4% and 100%)	10 d to 28 d of age	No effects on the BWG, FI and FCR	Cullere et al., 2016

HI: *Hermatia illucens*; TM: *Tenebrio molitor*; ZM: *Zophobas mori*.

Nutrients digestibility

In most of the studies about insect fat substitution in broiler chicken nutrition, there were no effects on the coefficients of the apparent nutrient digestibility of crude protein and crude fat or the apparent metabolizable energy (Kierończyk et al., 2018; Benzertiha et al., 2019; Kierończyk et al., 2020). Furthermore, Sypniewski et al. (2020) did not report any effects on the coefficients of the apparent nutrient digestibility of crude protein and crude fat or on the apparent metabolizable energy in young turkeys after *H. illucens* oil supplementation in the diet.

Immune response and gut microbiota

Molecular analysis of the expression levels of metabolic- and immune-related genes in broiler liver indicate the upregulation of selected genes after supplementation of *T. molitor* and *Z. morio* oil (Kierończyk et al., 2018). For example, tenebrionid oils increase the mRNA expression levels of *APOA1*, one of the genes responsible for phenotypic fatness, *HNF4 α* , which participates in controlling lipid metabolism, and *GIMAP5*, a key factor in maintaining T cell homeostasis (Kierończyk et al., 2018; Zhang et al., 2020). Furthermore, Sypniewski et al. (2020) reported that *H. illucens* fat as a dietary energy source reduced the levels of IL-2 and TNF-alpha in the serum of young turkeys. The same authors observed that total replacement of soybean oil by *H. illucens* fat significantly reduced the potentially pathogenic bacteria in the jejunum, such as *Enterobacteriaceae* spp.

Serum biochemical parameters

H. illucens fat application in broiler chicken nutrition significantly reduced serum total cholesterol and HDL in comparison to groups fed diets supplemented with coconut oil (Kim et al., 2020). In addition, in our previous study (Benzertiha et al., 2019), broiler chickens supplemented with *T. molitor* oil showed a lower triglycerides level in the blood in comparison to birds supplemented with palm oil and poultry fat. Sypniewski et al. (2020) reported that serum total cholesterol, HDL, and LDL of young turkeys supplemented with *H. illucens* fat as a replacement for soybean oil were significantly decreased in comparison to groups fed diets supplemented with soybean oil. The decreased levels in total cholesterol and HDL in the serum of birds fed with *H. illucens* fat-based diets may be due to the high level of MCFA in the *H. illucens* fat (Khatibjoo et al., 2018).

Final product quality

The substitution of insect fat (*T. molitor* oil, *H. illucens* fat, and *Z. morio* oil) in poultry diets and its impact on the final product quality were tested in several studies through the investigation of product quality traits and the FA profiles of different tissues (Kierończyk et al., 2018; Benzertiha et al., 2019; Cullere et al., 2019 a; Kierończyk et al., 2020; Kim et al., 2020). As mentioned previously, the FA profile of the insect species can vary greatly due to several factors, and these variations can have a direct effect on the profile of the meat and other tissues. It is also reported that *H. illucens* fat is highly rich in saturated fatty acids, which could have a negative impact on the FA profile of the final products. Cullere et al. (2019 a) limited the fat supplementation to the finisher period (21 to 48 day of age) of broiler chicken, in which an experiment with total and partial replacement of soybean oil by *H. illucens*

fat (50%, 100%) was conducted. The authors reported that the dietary treatments significantly affected the fatty acids profile of the breast muscle due to the higher SFAs in diets supplemented with *H. illucens* fat than soybean oil (45.8%, 36.5%, 28.8% for 100% *H. illucens* fat, 50% *H. illucens* fat; 100% soybean oil, respectively). The same findings were also noted on the thigh tissue FA profile. Furthermore, the authors did not find any effects of the dietary treatments on the chemical and physico-chemical qualities of the thigh meat. These effects may be related to the high level of SFAs in the diets of the birds. Furthermore, Kim et al. (2020) reported that the pH value of the breast meat of broiler chicken at 30 days of age was significantly affected by dietary treatments in which *H. illucens* fat and corn oil significantly increased in value compared to coconut oil. Further the yellowness was increased in the case of *H. illucens* fat and coconut oil treatments compared to corn oil. However, the authors stated that all analyzed parameters of breast and thigh meat, i.e., meat color, pH, and cooking loss, were within the range of the acceptable meat characteristics. As mentioned previously, *T. molitor* oil is highly rich in UFAs and is highly enriched in essential FAs such as linoleic acid (C18:2 cis 9,12). Kierończyk et al. (2018) and Benzertihá et al. (2019) reported that *T. molitor* oil supplemented in the diet of broiler chicken had the same effect on the breast muscle and liver tissues by improving their quality in terms of FA profiles. The authors concluded that *T. molitor* oil can be applied in broiler chicken nutrition without any adverse effects on the final product quality. Furthermore, 15% *H. illucens* full-fat meal addition to the broiler quail diets increased the cooking loss and the tenderness and decreased the pH value and the redness of the breast meat in comparison to the group supplemented with soybean meal and oil (Cullere et al., 2016, 2017; Dalle Zotte et al., 2019). In addition, the BSF full-fat meal influenced the FA composition in breast meat by increasing the SFA content. Moreover, research by Harlystiarini et al. (2020) indicated the positive effect of BSF full-fat meal on egg production and egg mass in quails. However, as reported by Dalle Zotte et al. (2019), *H. illucens* full-fat meal at a 15% inclusion increased the SFA and MUFA profiles and decreased the PUFA and omega 3 FA levels of the eggs compared to groups without *H. illucens* full-fat meal supplementation. It should be mentioned that in the case of insect full-fat meal, other characteristic components, such as chitin, may strongly influence the observed results.

Fish

In the last two decades, studies on insect application in fish nutrition have continuously developed in terms of experimental data for new species, forms, and technologies of preparation of insect-derived feed materials (Tschirner and Kloas, 2017; Gasco et al., 2019 c). Insects were tested in the diet of farmed fish (Józefiak et al., 2019 a, b), ornamental species (Vargas-Abúndez et al., 2019), laboratory fish models (Vargas et al., 2018) as well as aquatic invertebrates (Motte et al., 2019). They are part of feeding practice in ornamental (James, 2019) fish feeding, as well as other aquatic and semiaquatic pets (Rawski et al., 2018). It should be emphasized that insects as a novel feed ingredient in farm animal diets will be used on a large scale mainly in aquafeeds due to the fact that the legislation process (in the EU) is fastest for both protein and fat (no restrictions) usage. Four forms of insect products are

seen in the literature: full-fat insect meals (Nogales-Mérida et al., 2018; Józefiak et al., 2019 a, b), defatted meals (Renna et al., 2017), hydrolyzed meals (Hoffmann et al., 2020) and fats (Li et al., 2016; Dumas et al., 2018; Belghit et al., 2018). In aquaculture nutrition, according to the available literature, scientists focus mainly on the replacement of the current protein resources. While only one kind insect fat was studied, there have been trials on the use of *H. illucens* fat as a replacement for rapeseed, fish, and soybean oils performed on Atlantic salmon (*Salmo salar*), rainbow trout (*Oncorhynchus mykiss*) and Jian carp (*Cyprinus carpio* var. Jian), respectively (Belghit et al., 2018; Dumas et al., 2018; Li et al., 2016). In the case of Atlantic salmon, two sources of *H. illucens* oil were used: IO1 from larvae grown on organic waste streams and IO2 on seaweeds; they were used as rapeseed oil alone or in combination with *H. illucens* meal (Belghit et al., 2018). There were no observed effects of fat source on voluntary FI, indicating no negative effect on feed palatability, as well as final body weight (FBW), FCR, protein efficiency ratio (PER), and Fulton's body condition factor K. However, the daily growth index (DGI) and specific growth ratio (SGR) were decreased by IO1 in comparison to the control diet (rapeseed and fish oil) IO2. No significant correlation among protein and fat sources was observed. The source of fat showed a significant effect in crude lipid digestibility – IO1 decreased it in comparison to both IO2 and rapeseed oil. The activity of the gastrointestinal tract was not affected in terms of trypsin and bile acid secretion; however, reduced activity of leucine aminopeptidase was observed in distal intestine tissue. In terms of whole fish body composition, dry matter, crude protein and lipid levels were unaffected by insect oil addition (Belghit et al., 2018). Mineral components of the body and most amino acids remained unaffected by the diet, except alanine, asparagine, glutamine, leucine, lysine and valine, which were increased in fish fed insect lipids. Most importantly, the study showed that protein and fat resources are successfully replaced by insects' oil and meal in Atlantic salmon diet. In the case of rainbow trout, fish oil was replaced by 2.5, 5, and 10% of *H. illucens* fat mechanically extracted from larvae grown on undescribed feedstock (Dumas et al., 2018). However, no information about feed production issues or feed water stability was given, and feed produced with insect oil addition was characterized by a lower bulk density and a higher percentage of floating pellets, suggesting a higher post-extrusion expansion level. The growth performance, feed utilization parameters, and somatic indices were not impaired, including FBW, FI, FCR, BWG, thermal-unit growth coefficient (TGC) survival rate, and hepatosomatic index. In terms of whole-body composition, crude lipids and hydroxyproline were increased by the incorporation of 5% of insect oil to the diet, with no effect on fillet composition. *H. illucens* fat in the highest used rate (10%) significantly reduced lipid deposition, while the numerically highest value was observed at the middle dose (5%). No significant effect was observed in terms of intestinal histomorphology – villus length and width of anterior as well as posterior intestine. Blood plasma analysis showed a decreased glucose level as a consequence of 10% insect oil incorporation, but no effects on other biochemical parameters, including cholesterol, creatinine kinase, total protein, albumin, globulin, bilirubin and hematocrit as well as mineral levels (K, Na, Cl, Ca, P, Mg). No effect was observed in terms of protein, lipid, dry matter and the apparent digestibility

coefficients of most amino acids except for an increase in the case of hydroxyproline. In most studies on the application of insect-derived components in fish diets, carnivorous fish species are used due to high protein requirements. However, when fat is taken under consideration, herbivorous and carnivorous species should also be included. The best example of that is common carp (*Cyprinus carpio*) and its local varieties, which have low nutritional demand, but the large scale of production, especially in Asia, may create a high market demand on dietary fats. Li et al. (2016) replaced 25%, 50%, 75% and 100% of soybean oil by up to 2.5% of black soldier fly fat in juvenile Jian carp (*Cyprinus carpio* var. Jian) diet prepared with a cold press technique. No information about feed quality was given, but the levels of FI suggest that it was slightly better accepted than control diet. Thus, it may be suggested that insect fat or insect flavor in general may be a nutritional attractant for some fish species, which was earlier proven in sturgeons and common carp (Kasumyan, 2018). In the study of Li et al. (2016), there were no effects of treatment on growth performance and feed utilization indices, including FBW, SGR, FCR, and condition factor, as well as somatic indices, including viscerosomatic and hepatosomatic indices. The intraperitoneal fat index was reduced by 75 and 100% of *H. illucens* oil inclusions. The proximate compositions of whole-body, muscle, hepatopancreas, and blood serum biochemical indices were not affected. In terms of the fatty acid composition of muscle, hepatopancreas and intraperitoneal fat, all tissues were enriched in 12:0, 14:0 and SFA as well as 22:6n3 in muscles. Total n3 PUFAs were slightly enhanced by increasing insect oil incorporation, while n6 PUFAs were reduced in muscles and intraperitoneal fat. The last of the mentioned tissues was also affected in terms of decreasing adipocyte size by 75% and 100% insect fat inclusion. Chen et al. (2017) replaced soybean oil with silkworm chrysalis oil in juvenile Jian carp nutrition. The fat inclusion level in the diet was 3% with a 25%, 50%, 75%, and 100% replacement of soybean oil by silkworm oil. The authors reported that 75% and 100% of silkworm chrysalis oil inclusion to the diet had a positive effect on the growth performance and the feed utilization. Moreover, 100% inclusion of silkworm chrysalis oil to the diet of juvenile Jian carp significantly increased the omega 3 PUFAs and the n3/n6 ratios in the muscle, intraperitoneal fat, and hepatopancreas.

The studies published to date provide a scarce spectrum of insect fat use in fish diet examples. The inclusions of oil provided to fish diets varied from below 3% in low requirement species to 4.6% in carp and 12% in salmonids. However, insect oils have higher potential in sustainable fish nutrition than protein due to the possibility of total replacement of environmentally unbalanced fat sources with no negative effects. However, more studies are needed to understand their role in fish physiology and nutrition for application in aquaculture industry, including health benefits (i.e., high content of lauric acid) and fatty acid composition-modifying properties.

Other livestock animals

Currently, in the available literature, only a few papers have investigated the effects of insect fat supplementation in the diet of other livestock animals. These researches mainly concern *H. illucens* and *T. molitor* lipids as a partial or total re-

placement of the fat resource in rabbit and nursery pig diets (Dalle Zotte et al., 2018; Martins et al., 2018; Gasco et al., 2019 a, b; Heugten et al., 2019).

Martins et al. (2018) indicated that *H. illucens* larvae fat can be an alternative to linseed oil in growing rabbits' diet without altering the growth performance and the carcass yield. Furthermore, *H. illucens* larvae fat did not have any effects on the total tract apparent digestibility of nutrients. However, in a similar experiment, performed by Dalle Zotte et al. (2018), *H. illucens* larvae fat significantly increased the levels of lauric and myristic acids of the thigh meat compared to linseed oil, while no effect was observed on the SFAs of the thigh meat. *H. illucens* larvae fat showed reduced PUFA and MUFA contents in the thigh meat compared to linseed oil. The lightness and yellowness of the *musculus longissimus lumborum* was not affected by the dietary treatments, though the redness was increased in groups supplemented with *H. illucens* larvae fat compared with those supplemented with linseed oil. Gasco et al. (2019 a, b) supplemented *T. molitor* oil and *H. illucens* fat in the growing rabbits' diets as a partial or total replacement of soybean oil. The authors did not observe any differences among dietary treatments on the growth performance traits. Further, no effects on the digestibility of nutrients and energy were noted. *T. molitor* oil and *H. illucens* fat did not have any effects on the carcass characteristics or the meat quality traits. Moreover, *H. illucens* fat addition increased the levels of SFAs and the n6/n3 PUFA ratios in *musculus longissimus thoracis et lumborum* of the rabbits compared with groups supplemented with soybean oil and *T. molitor* oil. From the above-mentioned studies, it can be summarized that *H. illucens* larvae fat and *T. molitor* oil can be an alternative source of fat in rabbits without altering the growth performance and the nutrient digestibility; however, the meat quality was worsened in the case of *H. illucens* fat supplementation due to the high level of SFAs. Therefore, a partial supplementation of *H. illucens* fat with a combined vegetable oil or enriching the *H. illucens* larvae fat with profitable FAs such as n3 PUFAs would be recommended in this case to avoid the negative effect on the meat quality of rabbits.

Research performed by Heugten et al. (2019) showed that BSF oil can also be a promising, high-energy feed ingredient for nursery pigs. Replacement of corn oil by BSF oil caused a linear increase in nursery pig body weight and, compared to corn oil treatment, did not significantly affect serological and hematological parameters, such as serum concentrations of total protein, glucose, triglycerides and different blood cell counts. Only in cases of serum cholesterol and platelet count were significant increases reported after BSF oil supplementation. Despite these exceptions, all tested parameters were in normal, expected ranges (Heugten et al., 2019).

Conclusions

Insect fats can be a sustainable source of energy for poultry, fish, and other livestock animals. Moreover, some results also indicate their positive effects mainly by the stimulation of immune system activity. However, despite the increasing research interests in insect biomass applications in livestock nutrition, information about fat supplementation is still limited.

In the published literature, more information is becoming available regarding the usage of insect fats in animal nutrition, mostly focusing on their effects on perfor-

mance, meat quality and digestibility. It is suggested that more attention and research should focus on the possible mode of action and immune-related genes involved in fat metabolism. Moreover, it should also be emphasized that the research concerning these issues not only will focus on the evaluation of insect fat application in animal production but also should strive to develop rearing/feeding programs for insects to modulate their lipid profile. The nutritive values of the insect fats are strictly related to the substrates used in insect production.

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