

Insect meals in fish nutrition

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Abstract

Different studies have shown that insect meals can partially or completely replace the fish and soya bean meals that are commonly used in aquaculture. However, information is lacking on the amino acid and fatty acid contents and digestibility of different insect meals. Moreover, we evaluated different proportions of insect diets and determined how these affected the nutritional values of insect meals. Our purpose was to clarify these aspects and consider the availability of protein, amino acids, lipids and fatty acids in insect meals in fish nutrition. Generally, insect meals have higher indispensable amino acid contents than other meal types, with contents closely related to those in fish meal. Insect meal can be an important source of essential amino acids such as methionine, with contents ranging between 0.47 and 4.03 g 100 g⁻¹ sample. These values are higher than those reported for other animal and plant meals. In addition, insects are also good sources of lipids and fatty acids, and the amounts and types of fatty acids vary according to the species, stage of development and type of feed. Moreover, the additional nutritional value of insect meal includes compounds such as chitin, which is primarily considered a fibre but also contains nitrogen and amino acids. Insect peptides with activity against pathogenic microflora provide secondary biological effects, which may significantly improve animal health.

Key words: alternative protein source, antimicrobial peptides, chitin, indispensable and dispensable amino acids, lipids and fatty acids.

Introduction

In recent years, insects have begun to play an important role in aquaculture as alternative protein sources (Stamer 2015). Insects are the most diverse group of animals in the world, and according to Chapman (2009), the total number of insect species is approximately one million. This group is part of the natural diets of carnivorous and omnivorous fish (Henry *et al.* 2015) in addition to other farm animals. Particularly during the larval and fingerling stages of fish rearing, different insect species are very important components of fish diets. Insects are found in most aquatic environments; however, in the open sea, only one genus, *Halobates*, occurs, and two genera, *Hermatobates* and *Halovelina*, live in the coral reef and tide pool marine environments (Andersen 1999; Voshell 2009). According to this information, insects are valuable protein sources in fish nutrition under natural

conditions due to their protein contents, which can range between 9.3% and 76% (Finke 2002; Makkar *et al.* 2014; Sánchez-Muros *et al.* 2014; Payne *et al.* 2015), and fat contents, which can vary from 7.9% to 40% (Barker *et al.* 1998; Finke 2015; Meneguz *et al.* 2018). These variations will affect the fatty acid and amino acid contents.

However, omnivorous and carnivorous fish require more protein in their diets than required by herbivorous or detritivorous species. According to Wilson (2002), the protein requirements for carnivorous fish are between 55% and 45% crude protein (CP), and the CP requirements for omnivorous fish are between 45% and 35%; these ranges contrast with those of other monogastric vertebrates that range between 12% and 30% (Table 1). The protein requirements of fish are strictly related to their amino acid profiles, and these requirements are based on the corporal amino acid profile of each species (Kaushik & Seiliez 2010).

Table 1 The relation of different fish species vs. their insect natural prey

Fish species	Fish growth stage	Insects species	Percentage	Authors
Channel catfish (<i>Ictalurus punctatus</i>)	Juveniles	Small insects. Chironomidae larvae and pupae	ND	Darnell (1958)
Brown trout (<i>Salmo trutta</i>)	All stages	Plecoptera	9–14	Elliot (1967)
From 0 to more than 2 years old.		Ephemeroptera	4–23	
		Trichoptera	0–55	
		Megaloptera	0–1	
		Diptera	3–11.5	
		Coleoptera	5–16	
		Hemiptera		
Common carp (<i>Cyprinus carpio</i>)	Juveniles, adults	Hemiptera (<i>Corixa</i> sp., <i>Notonecta</i> sp.)	5.14	Spataru et al. (1980)
		Diptera	2.2	
		Ceratopogonidae (<i>Sphaeromyias</i> sp.)	4.40	
		Chironomidae larvae and pupae (<i>Nilodorum brevibuca</i> , <i>Dicrotendipes</i> sp., <i>Einfeldia disparilis</i> , <i>Leptochironomus stilifer</i> , <i>Polypedilum tiberialis</i>)	95.58	
Turbot (<i>Scophthalmus maximus</i>)	Juveniles	Chironomidae		Aarnio et al. (1996)
White sturgeon (<i>Acipenser transmontanus</i>)	Fingerlings, juveniles	Ceratopogonidae larvae	4	Muir et al. (2000)
		Diptera larvae and pupae	4.7	
		Ephemeroptera	0.1	
Gilthead seabream (<i>Sparus aurata</i>)		Crustacea (ND)	22.6	Pita et al. (2002)
Pirarucu (<i>Arapaima gigas</i>)	Fingerlings, Juveniles	No insect reported		Oliveira et al. (2005)
		Insect remains	21	
		Hemiptera	4	
		Coleoptera	3	
Matrixia (<i>Brycon amazonicus</i>)	ND	Diptera	0.3	Zaniboni Filho et al. (2006)
		Insects	ND	
Atlantic Salmon (<i>Salmo salar</i>)		Ephemeroptera (Mayfly larvae)	41.9	Orlov et al. (2006)
		Trichoptera larvae	23.8	
		Diptera larvae (Simuliidae and Chironomidae)	0.4	
		Pupae (Chironomidae and Trichoptera)	1.2	
		Imagoes (aerial insects)	24.2	
Rainbow trout (<i>Oncorhynchus mykiss</i>)	All stages	Insects	ND	Adams et al. (2008), Ferriz et al. (2010)
		Chironomidae larvae,		
		Trichoptera larvae		
		<i>Belostoma</i> sp.		
		Odonata nymphs		
		Adults and larvae of Coleoptera		
Eel (<i>Anguilla anguilla</i>)	Juveniles, adults	Insects (adults and aquatic larvae)	ND	Bouchereau et al. (2009)
		Chironomidae, Diptera		
Nile Tilapia (<i>Oreochromis niloticus</i>)	All stages	Insect parts (ND)	13.87	Abdulhakim et al. (2015), Vidotto-Magnoni and Carvalho (2009)
Cachama (<i>Colossoma macropomum</i>)	Juveniles	Insects (ND)	ND	Ulrich (2017)

ND, Not defined by authors.

Because of the high protein requirements of fish, fish meal (FM) and soya bean meal (SBM) have become the primary protein sources. However, in the last decade, FM and SBM

have increased in price along with the other protein sources used in feed due to an increase in the global protein demand. This demand has increased because protein

sources are commodities used in feeds for livestock, companion animals and farmed fish (Hardy 2010), which are designated to meet the global demands of human population growth (Tilman *et al.* 2011). The increases in the price of protein sources used in livestock production are related to different factors: (i) increase or decrease in demand; (ii) weather conditions that affect the capture of fish used in fish meal production; (iii) weather conditions that affect vegetable farming; and (iv) most of the agricultural commodities used in fish farming are also generally used in animal farming in addition to human nutrition use.

Additionally, fish farming has grown by more than 200% in recent decades as a result of consumer demand (FAO, 2017). Fish is considered the healthiest meat because it is low in fat and rich in highly unsaturated fatty acids (HUFAs; Valfré *et al.* 2003), and fish has particular health benefits to children (Dubnov-Raz & Berry 2007; Le *et al.* 2009). Fish meat is also a source of valuable protein and provides a well-balanced amino acid profile for animal and human health that promotes many beneficial effects, including those provided by fish oil (Bell & Waagbø 2008).

For all these reasons, fish consumption has consistently increased, and since 2014, the world population has consumed more farmed fish than captured fish (FAO 2016). As a result, the limited availability of FM has led to increased efforts to identify fish meal replacements, and these efforts include analyses of all possible physiological or metabolic consequences (Kaushik & Seiliez 2010). Additionally, with the use of new alternative raw materials, fish costs will decline. Plant meals have been the most common replacement for FM, but plant meals can result in health problems caused by protein and amino acid (AA) deficiencies that impair immune function and increase the susceptibility of animals to infectious diseases (Oliva-Teles 2012). The contents of starch and antinutritional compounds in plant meals also cause health problems in farmed fish (Francis *et al.* 2001). The different plant meals used in fish nutrition, such as SBM, copra meal, sunflower meal, cotton meal and pea meal, are not parts of natural fish diets, and therefore, their protein contents and AA profiles are not well balanced for fish. Animal by-products such as blood meal, hydrolysed feather meal, bone meal and meat meal have also been used in fish nutrition (El-Haroun & Bureau 2007; Campos *et al.* 2017; Moutinho *et al.* 2017). In contrast to the plant meals used in fish nutrition, insects farmed under controlled conditions can be a viable alternative protein source in fish diets. To date, the protein and amino acid functions and the benefits of insect meals in fish nutrition have not been reviewed. Hence, the aim of this review was to analyse the benefits of insect protein and lipids in fish nutrition, with special attention to the balance of amino acids, amino acid scores, digestibility, some amino acid antagonists, chitin, antimicrobial peptides (AMPs) and the

type of fatty acids present in some insect meals. We also examine how different diets affect the quality and quantity of protein, amino acids, lipids and fatty acids in insect meals.

Insects as natural fish prey

Insects are much of the basic prey for omnivorous and carnivorous fish (Table 1; Badola & Singh 1980; Carolsfeld *et al.* 2003; Henry *et al.* 2015) and include aquatic insects in the adult and/or larval stages in the orders Diptera, Trichoptera, Odonata, Hemiptera, Coleoptera and Ephemeroptera (Ribeiro *et al.* 2014; Costa & Soares 2015; Pereira Neves *et al.* 2015; Severo-Neto *et al.* 2015; Abilhoa *et al.* 2016) and terrestrial insects that primarily belong to the families Vespidae and Formicidae (Dyer *et al.* 2015; Ferrareze *et al.* 2015). Some insects in the orders Hymenoptera, Diptera and Coleoptera have also been found in the guts of marine or brackish fish (Darnell 1958; Elliot 1967; Dyer *et al.* 2015). Insects are a well-documented part of fish diets, particularly in the early stages for carnivorous and omnivorous species, and are components of the diets of continental fish (Spataru *et al.* 1980; Oliveira *et al.* 2005; Abdulhakim *et al.* 2015; Ulrich 2017) as well as marine fish and fish that tolerate a wide range of salinity that can be found in brackish water (Darnell 1958; Dyer *et al.* 2015). Some fish species opportunistically feed on insects when food is abundant (Carolsfeld *et al.* 2003). Insects provide required essential amino acids, fatty acids, vitamins and certain minerals; however, little is known about the potential roles of chitin and AMPs.

Fish and other vertebrates have mouths adapted to select for insect prey. For example, one picker (*Labidochromis vellicans*) has a narrow mouth with long, recurved teeth that can be used as forceps to seize small insects; other species such as sturgeon have sucker-shaped mouths that point downward and are used to eat immature insects, and others, such as *Polyodon spathula* adults, use a large filtering network of gill rakers to feed on insect larvae and microcrustaceans. Nevertheless, most fish, for example, rainbow trout (*Oncorhynchus mykiss*), *Astyanax paraguayae* and *Oligosarcus hepsetus*, have wide mouths to inhale insects (Gerking 1994; Silva-Camacho *et al.* 2014). Another important adaptation is the digestive tract systems of carnivorous and omnivorous fish; the gastrointestinal tracts (GIT) of many fish have chitinase to aid in insect consumption. Chitinase is an enzyme produced by gastric glands and the pancreas and is required to digest chitin from insects and crustaceans (Rangaswamy 2006). Other chitinase enzymes are in some fish stomachs and perform well in acidic environments (Matsumiya *et al.* 2006).

External and behavioural adaptations have also been found, such as the adaptation observed in archerfish (*Toxotes jaculatrix*; *Toxotes chatareus*) to hunt insects (Bekoff &

Dorr 1976; Simon *et al.* 2009); additionally, in the cases of the arawana (*Osteoglossum bicirrhosum*) and the Pacific foureyes fish (*Anableps dowi*) fish, individuals jump approximately 1 m out of the water to catch large insects, which compose the primary diet (Miller 1979; Torres Del Castillo *et al.* 2012). Finally, as Gerking (1994) commented, all piscivorous fish can and will eat insects when that food source is abundant.

The digestive chitinase, buccal organ modifications and behavioural adaptations of fish show that insects and other arthropods have been parts of natural fish diets since pre-historic times, as Maisey (1994) showed in *Dastilbe* spp., which is an extinct fish from the Lower Cretaceous.

The protein and lipid contents in insect meals

Insects, as well as other animals, are good sources of protein, lipids, vitamins and minerals, but the amounts of these nutrients will vary according to the diet and the stage of the animal. Table 2 provides the variability due to the factors mentioned previously in five insect species, such as *Tenebrio molitor* (TM) larvae, whose crude protein content varies from 83.0 to 598.1 g kg⁻¹. In the case of *Hermetia illucens* (HI), the CP amount varies from 307.5 to 588.0 g kg⁻¹. In *Musca domestica* (MD), the CP amount can vary from 286.3 to 704.0 g kg⁻¹. In *Zophobas morio* (ZM), the amount of CP varies from 69.0 to 502.7 g kg⁻¹, and in *Acheta domesticus* (AD), the amount of CP varies from 88.0 to 641.0 g kg⁻¹.

The same variations are observed in the crude lipid (CL) contents of the same species, such as in HI, which has a CL content that can vary from 113.0 to 407.0 g kg⁻¹ or TM, which has a CL content that can vary from 166.0 to 403.0 g kg⁻¹. Similar variations have been observed in AD, in which the CL content varies from 79.0 to 240.0 g kg⁻¹, and in MD, the CL content varies from 70.6 to 253.0 g kg⁻¹. Nevertheless, the CL content in ZM seems to remain constant from 389.2 to 417.8 g kg⁻¹.

This variability will directly affect the contents of insect meal, resulting in different results from the same insect species, that is, Xiao *et al.* (2018) used HI larvae meal with a CP content of 47.0 g kg⁻¹ in *Pelteobagrus fulvidraco*, and they replaced FM with up to 100% HI meal 100%, obtaining the best growth performance with 25% replacement. In contrast, Belghit *et al.* (2018) tested replacement of up to 85% in *Salmo salar* without any significant differences among replacement levels.

The variability in the results obtained by researchers using the same insect meal sources should be related to more than the amount of protein, which, according to Jonas-Levi and Martinez (2017), is overestimated because of chitin presence. The use of insects in fish nutrition should be based on the amount of amino acids because this amount is available for fish consumption.

There are a few studies related to digestibility in fish nutrition (Fig. 1a,b) that used insects as protein and/or energy sources, and among them, we can observe that the HI meal obtained relatively higher levels of CP digestibility (81.10–97.00%) than those obtained in TM meal (79.19–92.00%) or ZM meal, which obtained the lowest values (50.53%). The levels of inclusion varied from 13% to 100%, which was the case for HI meal. This higher inclusion caused a marked reduction in the apparent digestibility of crude protein (ADCP) (63.10%). In the case of crude lipid digestibility (ADCL), all insect meals presented higher lipid digestibility values than protein digestibility values. TM meal presented higher digestibility values from 82.39% to 97.00%.

The amino acid profiles of insect meals

In fish nutrition, 10 amino acids are considered indispensable: arginine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan and valine. As mentioned above, the amount of protein in insect bodies varies according to the stage of development (larva, pupa, prepupa, imago), the type of diet and the rearing conditions, and as a consequence of these variations, the amino acid contents can also vary, as shown by Finke (2002) in the case of AD in which the lysine content varied from 1.10 g 100 g⁻¹ sample in adults and 0.83 g 100 g⁻¹ sample in nymphs (expressed in wet weight). However, Spranghers *et al.* (2017) showed that the lysine contents of HI fed with different diets varied from 2.30 to 2.57 g 100 g⁻¹ sample (expressed in wet weight). Although the highest variations seem to be more marked in the dispensable amino acids (DAA), that is, glutamic acid, the contents varied from 3.98 to 4.58 g 100 g⁻¹ sample (Spranghers *et al.* 2017).

Amino acids: indispensable amino acid (IAA) contents and digestibility

The comparisons among SBM, fish meal and insect meals show that fish demands could be met by these alternative sources. Nevertheless, significant differences have been found among meals and types of amino acids, as shown in Table 3. The availability of these amino acids depends not only on the raw material content but also on the process used to obtain these materials. Nunes *et al.* (2014) commented that global fish meal supplies must be processed using drying and grinding, applying chemicals to extract parts of the nutritional components, or cooking or fermentation. All of these factors determine the amount of protein available and the resulting amino acid composition and digestibility. Similarly, insect meal is processed using different drying methods or techniques to improve meal quality, as tested by Lock *et al.* (2016).

Table 2 Protein and lipid content of insect meals, expressed in g kg⁻¹ per sample, according to their growth stage and type of food proportionate

Insect species	Stage	Type of food received	Corporal composition			Authors
			Dry matter	Protein	Lipids	
<i>Tenebrio molitor</i>	Larvae	Wheat, grain, carrots	371.0	83.0	311.0	Barker <i>et al.</i> (1998)
<i>T. molitor</i>	Larvae	Wheat bran, unknown supplements	417.0	77.0	403.0	
<i>T. molitor</i>	Larvae	Fatty acids, vitamins E, β -carotene	311.0	598.1	263.7	Finke (2015) (on dry matter)
<i>T. molitor</i>	Larvae	Animals acquired from different companies: Gaobeidian Shannon	960.0	522.0	284.0	Marono <i>et al.</i>
<i>T. molitor</i>	Larvae	Biology Co., Ltda., Shandong, China; Kreca, the Netherlands;	958.0	518.0	298.0	(2015)
<i>T. molitor</i>	Larvae	EnviroFlight LCC, OH, USA	990.0	590.0	166.0	
<i>T. molitor</i>	Larvae		992.0	588.0	171.0	
<i>T. molitor</i>	Larvae		982.0	576.0	289.0	
<i>T. molitor</i>	Larvae		990.0	574.0	289.0	
<i>T. molitor</i>	Larvae	Cereal brans	349.6	584.2	300.9	Sánchez-Muros <i>et al.</i> (2016)
<i>Hermetia illucens</i>	Prepupae	Swine manure	916.0	436.0	331.0	St-Hilaire <i>et al.</i> (2007)
<i>H. illucens</i>	Larvae	Animals acquired from different companies: Enviroflight LCC, OH, USA;	951.0	520.0	113.0	Marono <i>et al.</i>
<i>H. illucens</i>	Larvae	Laboratory of Entomology, Wageningen University, the Netherlands.	948.0	518.0	113.0	(2015)
<i>H. illucens</i>	Larvae		988.0	588.0	129.0	
<i>H. illucens</i>	Larvae		989.0	584.0	290.0	
<i>H. illucens</i>	Larvae		959.0	499.0	284.0	
<i>H. illucens</i>	Larvae		959.0	505.0	249.0	
<i>H. illucens</i>	Larvae	Organic waste from food designed for human consumption (different	965.0	522.0	255.0	Lock <i>et al.</i> (2016)
<i>H. illucens</i>	Larvae	methods of obtaining the final product)	956.0	583.0	170.0	
<i>H. illucens</i>	Larvae	Chicken feed	387.0	412.0	336.0	Spranghers <i>et al.</i>
<i>H. illucens</i>	Larvae	Digestate	386.0	422.0	218.0	(2017)
<i>H. illucens</i>	Larvae	Vegetable waste	410.0	399.0	371.0	
<i>H. illucens</i>	Larvae	Restaurant waste	381.0	431.0	386.0	
<i>H. illucens</i>	Larvae	Brewery solid waste, water, wheat bran, yeast slurry, processing wastes	950.3	416.4	234.4	Devic <i>et al.</i> (2018)
<i>H. illucens</i>	Larvae	from fish feed factory				
<i>H. illucens</i>	Larvae	Vegetable-fruit waste	219.6	418.8	262.8	Meneguz <i>et al.</i>
<i>H. illucens</i>	Larvae	Fruit waste	282.9	307.5	407.0	(2018)
<i>H. illucens</i>	Larvae	Winery by-product	265.4	344.3	322.2	
<i>H. illucens</i>	Larvae	Brewery by-product	290.8	529.6	298.7	
<i>H. illucens</i>	Larvae	Fresh chicken manure		470.0	177.0	Xiao <i>et al.</i> (2018)
<i>Musca domestica</i>	Larvae	Poultry dropping	947.0	480.0	149.0	Ajani <i>et al.</i> (2004)
<i>M. domestica</i>	Pupae	Cow manure	881.0	704.0	161.0	St-Hilaire <i>et al.</i> (2007)
<i>M. domestica</i>	Larvae	Cattle blood, wheat bran	927.0	471.0	253.0	Aniebo <i>et al.</i> (2008)
<i>M. domestica</i>	Larvae	Poultry dropping	942.4	286.3	233.0	Ogunji <i>et al.</i> (2008)
<i>M. domestica</i>	Larvae	Bran and pork blood (1:2)		310.0	78.8	Pieterse and Pretorius (2014)
<i>M. domestica</i>	Prepupae	Bran and pork blood (1:2)		371.9	70.6	
<i>M. domestica</i>	Larvae	Soybean cake, chicken viscera		584.0		Djissou <i>et al.</i> (2016)
<i>M. domestica</i>	Larvae	Chicken manure		570.0		Kovtunova <i>et al.</i> (2017)
<i>M. domestica</i>	Larvae	Chicken manure, selenium 5 mg kg ⁻¹		550.0		
<i>M. domestica</i>	Larvae	Chicken manure, selenium 15 mg kg ⁻¹		510.0		
<i>M. domestica</i>	Larvae	Chicken manure, selenium + cobaltum 5 mg kg ⁻¹		594.2		

Table 2 (continued)

Insect species	Stage	Type of food received	Corporal composition			Authors
			Dry matter	Protein	Lipids	
<i>M. domestica</i>	Larvae	Chicken manure, selenium + cobaltum 15 mg kg ⁻¹		617.2		
<i>M. domestica</i>	Larvae	Wheat bran wet (moisture 600–700 g kg ⁻¹)	934.3	566.1	205.0	Wang <i>et al.</i> (2017)
<i>Zophobas morio</i>	Larvae	Wheat grain, carrots	430.0	69.0	408.0	Barker <i>et al.</i> (1998)
<i>Z. morio</i>	Larvae	Base diet, flaxseed, canola oil, fish oil, corn gluten meal, yellow carotenoid supplement, vitamin E, thiamin, β-carotene	370.0	502.7	389.2	Finke (2015) (on dry matter)
<i>Z. morio</i>	Larvae	Kelp granulate	499.0	448.1	417.8	Nederlof <i>et al.</i> (2017)
<i>Z. morio</i>	Larvae	Oat meal	473.0	450.4	402.3	
<i>Acheta domestica</i>	adults	Corn meal, wheat midds, soybean hulls, meat meal, molasses, fish meal	268.0	103.0	228.0	Barker <i>et al.</i> (1998)
<i>A. domesticus</i>	Nymphs	Corn meal, wheat midds, soybean hulls, meat meal, molasses, fish meal	332.0	88.0	98.0	
<i>A. domesticus</i>	Adults	Wild animals capture		641.0	240.0	Ramos-Elorduy Blásquez <i>et al.</i> (2012)
<i>A. domesticus</i>	Nymphs	Base diet, flaxseed, canola oil, fish oil, corn gluten meal, yellow carotenoid supplement, vitamin E, thiamin, β-carotene	275.0	165.0	79.0	Finke (2015) (on dry matter)

Arginine

In insect meals, the arginine (Arg) content exhibited great variability from 1.94 to 6.06 g 100 g⁻¹ sample (Table 3). The highest value obtained was in MD larvae fed with a mix of soya bean cake and chicken viscera (Djissou *et al.* 2016). Considering the results of Zhao *et al.* (2012, 2017), even the lowest value could cover fish demands, which were between 8.6 and 18.1 g kg⁻¹ depending on the fish species. Moreover, Renna *et al.* (2017) found that a decreasing amount of Arg due to the inclusion of HI meals did not affect the growth performance of rainbow trout fed with 10%, 25% and 50% HI meal. Magalhães *et al.* (2017) also showed that even with the maximum inclusion of HI meal in the diet of *Dicentrarchus labrax*, the digestibility of this IAA was higher than that in FM. In addition, comparing the Arg digestibility of a few insect meals, we found that it varies from 91% to 98.1% depending on the insect meal, the amount of inclusion, the target fish species and the age of the fish (Table 4).

Histidine

The histidine (His) content varied from 1.06 to 3.01 g 100 g⁻¹ sample depending on the insect species and the stage of development, which was similar to the case of HI larvae, which exhibited the lowest value (Table 3). However, even the lowest value was higher than the average value of SBM. This value could cover certain fish demands if we consider the findings of Khan and Abidi (2014)

related to this AA in *Heteropneustes fossilis*, and they affirmed that the optimal amount of His to achieve the maximum growth performance was 1.58 g 100 g⁻¹ sample. However, it was also observed that the inclusion of up to 43% of TM meal caused a reduction in the His content in the fillets of Nile tilapia in comparison with the control diet (Sánchez-Muros *et al.* 2016). Moreover, comparing the His digestibility among insect species and fish species, we observed higher variation than that observed for Arg digestibility, from 89% with 25% of HI meal in *S. salar* to 98.1% with 20% HI meal in *D. labrax* (Table 4).

Isoleucine

The content of this IAA in insect meals fluctuates from 1.06, which was detected in MD larvae meal, to 3.23 g 100 g⁻¹ sample in MD pupae meal (Table 3). These values seem sufficient to meet fish demands according to Gan *et al.* (2014), who found that 1.25 g 100 g⁻¹ sample in the diet was optimal to improve the growth performance and feed efficiency parameters. In addition, the Iso digestibility in insect meals, mainly in HI meal (Table 4), varies from 87.5% in *D. labrax* fed with 13% HI meal to 98.0% in *S. salar* fed with 12% HI oil.

Leucine

According to our revision, the leucine (Leu) content in insect meals varies from 2.18 g 100 g⁻¹ sample in MD

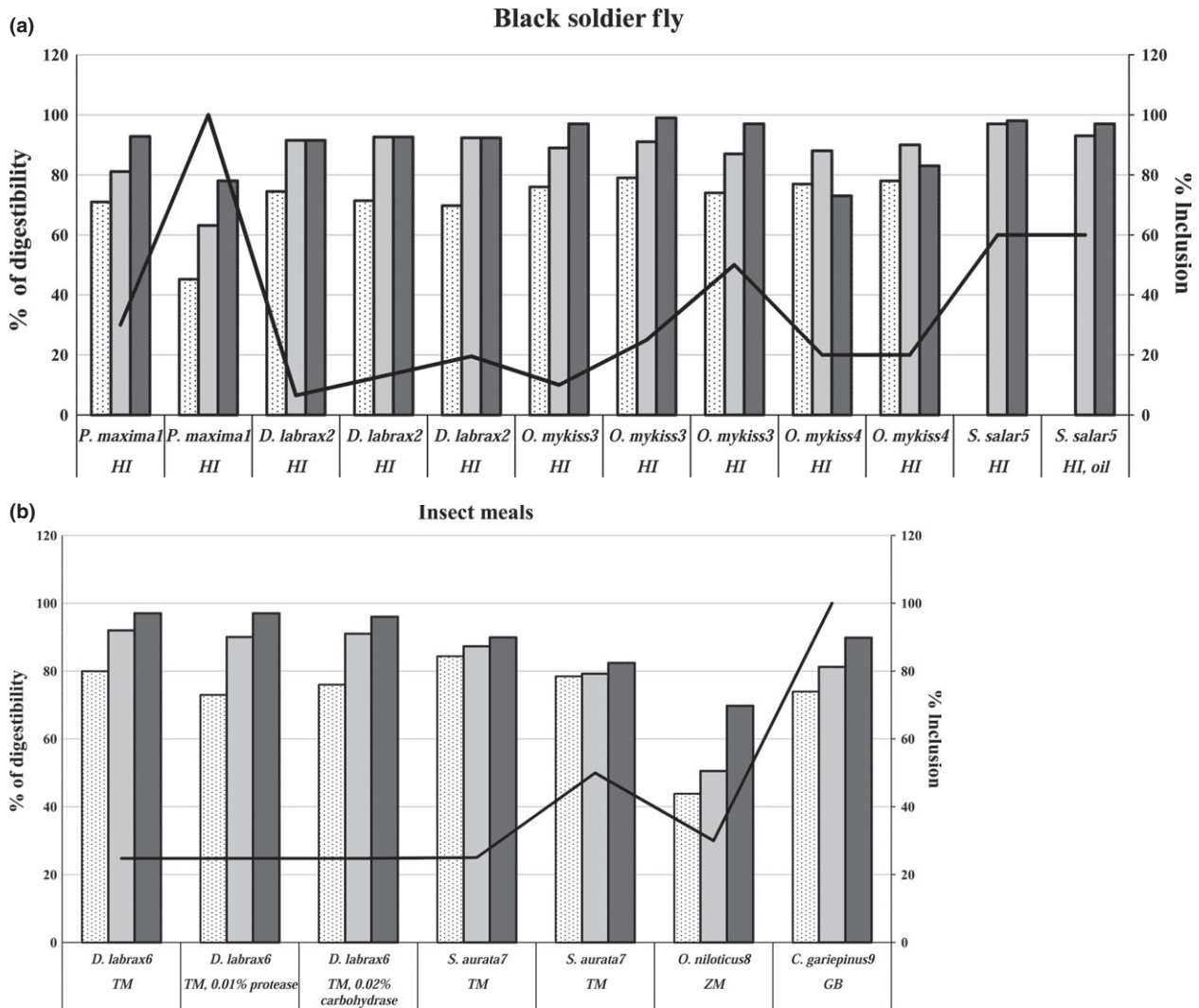


Figure 1 (a) Digestibility values of some fish species fed with *Hermetia illucens*. (b) Digestibility values of some fish species fed with *Tenebrio molitor*, *Zophobas morio* and *Gryllus bimaculatus* (b). ADDM = Apparent digestibility of dry matter; ADCP = Apparent digestibility of Crude protein; ADCL; Apparent digestibility of crude lipid. 1. Kroeckel *et al.* (2012); 2. Magalhães *et al.* (2017); 3. Renna *et al.* (2017); 4. Dumas *et al.* (2018); 5. Belghit *et al.* (2018); 6. Gasco *et al.* (2016); 7. Piccolo *et al.* (2017); 8. Jabir *et al.* (2012); 9. Taufek *et al.* (2016). (▨) ADDM; (□) ADCP; (■) ADCL; (—) % Inclusion.

larvae meal, and the highest value of 6.66 g 100 g⁻¹ sample occurred in AD adults (Table 3). All insect meals presented higher values than those presented by SBM and, in many cases, the values were similar to those found in FM. The amount of this IAA could be sufficient to cover the demands of fish, as Zehra and Khan (2017) found in Nile tilapia fingerlings fed with increasing levels of Leu, and the optimum level was 1.58%. Moreover, the digestibility of this IAA ranged from 88% obtained in *D. labrax* fed with 13% HI meal, and the highest values were found in *S. salar* fed with 12% HI oil inclusion (Table 4).

Lysine

The contents of lysine (Lys) in the different insect meals were much higher than those in SBM, and only two samples had values that were lower than those in SBM; one of these values was observed in MD larvae, and the other was observed in TM larvae. In addition, Hussein *et al.* (2017) and Hall *et al.* (2018) reported Lys values that were higher in insect meal than those found in FM. These results show the great variability that different insect meals generally possess. The Lys content ranged from 1.68 to 4.49 g 100 g⁻¹ sample (Table 3). This content seems sufficient to cover the needs of certain species, such as Atlantic

Table 3 Amino acid content of different insect meals used in aquaculture (data are expressed as g 100⁻¹ of sample in dry matter)

Spp	Stage	Arg	His	Ile	Leu	Lys	Met	Phe	Thr	Trp	Val	Ala	Asp	Cys	Glu	Gly	Pro	Ser	Tyr	Tau	IAA/DAA	Authors
MD	Larvae	2.35	1.21	1.06	2.18	1.68	0.47	1.32	0.88		2.15	1.51	0.64	0.08	0.00	1.03	1.56	0.91	1.27		1.90	Pieterse and Pretorius (2014)
MD	Larvae	6.06	3.01	3.05	6.35	4.23	1.82	3.53	2.09	3.17	1.91											Djissou et al. (2016)
MD	Larvae	3.17	1.59	1.84	3.28	3.85	4.03	3.82	2.49	0.69	2.59	2.91	5.18	0.78	8.38	2.22	2.49	2.25	3.51	0.26	0.98	Hussein et al. (2017)
MD	Larvae	3.02	1.82	2.26	3.83	4.49	1.58	3.78	3.32	4.10	2.70	3.47	6.21	1.74	8.44	2.83	2.38	1.58	4.07		1.01	Hall et al. (2018)
MD	Pupae	4.80	2.27	3.23	4.92	5.00	2.32	3.14	3.00	0.95	4.37	4.64	6.47	0.56	8.37	3.35	3.32	2.77	3.67	0.63	1.01	Finke (2012)
MD	Pupae	4.16	1.33	1.15	2.61	2.28	0.55	1.64	1.38		5.02	1.57	0.74	0.12	1.40	1.19	1.63	1.85	1.80		1.95	Pieterse and Pretorius (2014)
HI	Larvae	3.17	1.53	1.96	3.12	3.07	0.87	1.95	1.76	0.77	3.32	3.14	4.25	0.26	5.08	2.36	2.63	1.81	3.12	0.03	0.95	Finke (2012)
HI	Larvae	1.94	1.13	1.72	2.40	2.23	0.91	1.44	1.52		2.20	3.03	3.22	1.38	3.85	1.91	3.73	1.84	2.16		0.73	De Marco et al. (2015)
HI	Larvae	2.65	1.62	2.23	3.61	3.72	1.16	2.35	2.24	3.78	3.34	5.28			5.57	2.63	5.55	2.02	3.40		0.84	Li et al. (2017)
HI	Larvae	2.15	1.23	1.85	2.86	2.10	0.65	1.66	1.72	2.72	3.45	3.72	0.01	4.87	2.35	3.06	2.03	2.64			0.77	Schiavone et al. (2017)
HI	Larvae	2.70	1.63	2.40	3.67	2.52	0.86	2.18	2.18	3.45	4.37	4.88	0.02	6.37	3.03	3.27	2.68	3.41			0.77	
HI	Larvae	2.19	1.06	1.92	3.00	2.79	0.63	1.79	1.67	0.54			0.42							0.37		Dumas et al. (2018)
HI	Prepupae	2.03	1.36	1.72	2.86	2.34	0.76	1.70	1.64	0.67	2.41	2.52	3.78	0.25	4.19	2.26	2.25	1.66			1.03	Spranghers et al. (2017)
HI	Prepupae	2.03	1.35	1.84	2.95	2.57	0.87	1.87	1.68	0.62	2.49	2.43	3.36	0.24	3.98	2.56	2.21	1.55			1.12	
HI	Prepupae	2.00	1.24	1.73	2.80	2.26	0.76	1.63	1.54	0.58	2.48	2.42	3.59	0.21	4.13	2.22	2.14	1.50			1.05	
HI	Prepupae	1.99	1.38	1.91	3.06	2.30	0.71	1.64	1.62	0.54	2.82	2.78	3.69	0.22	4.58	2.52	2.51	1.59			1.00	
TM	Larvae	2.64	1.67	2.21	3.67	2.90	0.67	1.92	1.64	0.44	3.13	3.51	4.15	0.38	5.85	2.54	3.10	2.33	3.67	0.01	0.82	Finke (2002)
TM	Larvae	2.55	1.55	2.47	5.22	2.68	0.63	1.73	2.02	0.39	2.89	4.04	3.99	0.42	5.4	2.73	3.41	2.52	3.60	0.02	0.84	
TM	Larvae	2.90	1.93	2.93	5.57	2.98	0.85	1.76	2.30	0.74	4.26	5.14	4.72	0.45	6.48	5.68	4.26	2.78	2.24	0.00	0.83	Finke (2007)
TM	Larvae	2.80	1.68	2.21	3.15	3.59	1.01	1.88	1.85		2.82	3.89	4.37	1.25	6.29	2.21	3.43	2.27	3.28		0.78	De Marco et al. (2015)
TM	Larvae	4.44	1.80	2.68	4.50	3.44	0.82	2.10	2.43	0.69	4.12	5.27	4.89	0.52	6.85	3.22	2.77	2.43	3.83	0.00	0.91	Finke (2015)
TM	Larvae	2.03	1.07	1.39	2.81	1.86	0.54	1.36	1.57		3.14	3.15	3.07	0.35	4.57	2.04	2.23	1.86	2.63		0.79	Jin et al. (2016)
TM	Larvae	2.63	1.58	2.08	2.96	3.37	0.95	1.77	1.74		2.65	3.65	4.10	1.17	2.08	5.91	3.22	2.13	3.08		0.78	Iaconisi et al. (2017)
TM	Adult	2.46	1.64	2.48	4.72	2.53	0.72	1.49	1.95	0.63	3.61	4.36	4.00	0.39	5.49	4.82	3.61	2.36	1.90	0.03	0.82	Finke (2002)
TM	Adult	2.89	1.82	2.37	3.94	3.11	0.94	2.09	1.96	0.50	3.31	3.86	4.52	0.52	6.36	2.87	3.55	2.62	3.83	0.00	0.81	Finke (2007)
AD	Nymph	4.10	1.48	2.88	6.42	3.62	0.87	1.88	2.40	0.35	3.32	5.98	4.76	0.57	6.99	3.54	3.71	2.79	3.71	3.54	0.77	Finke (2002)
AD	Nymph	5.00	1.81	2.86	5.12	4.40	1.09	2.26	2.74	0.44	4.23	7.14	5.60	0.65	8.27	4.27	4.31	3.02	4.44	0.00	0.79	Finke (2007)
AD	Nymphs	4.95	1.32	2.42	4.25	3.48	1.00	2.13	2.26	0.52	3.58	5.45	4.73	0.59	6.87	3.21	3.59	2.43	3.89	0.07	0.84	Finke (2015)
AD	Adults	4.06	1.56	3.05	6.66	3.57	0.97	2.11	2.40	0.42	3.47	5.84	5.58	0.55	6.98	3.38	3.73	3.31	3.25	4.58	0.76	Finke (2002)
AD	Adults	4.06	1.60	2.58	4.72	3.62	1.38	2.14	2.20	0.53	3.43	5.44	6.01	0.69	7.39	3.21	3.84	3.68	3.11	0.00	0.79	Finke (2007)
ZM	Larvae	2.28	1.43	2.21	4.54	2.85	0.60	1.62	1.85	0.43	2.45	3.40	3.75	0.36	5.75	2.26	2.57	2.19	3.25	0.01	0.84	Finke (2002)
ZM	Larvae	3.49	1.60	2.38	3.68	2.89	0.60	2.02	2.02	0.55	3.32	3.89	4.38	0.47	6.59	2.51	2.86	2.19	3.54	0.00	0.86	Finke (2015)
ZM	Larvae	2.31	1.55	2.30	3.54	2.68	0.56	1.90	1.98	0.71	3.18	4.58	3.92	0.34	6.60	2.40	2.97	2.05	3.76	0.00	0.78	Nederlof et al. (2017)
ZM	Larvae	2.43	1.56	2.30	3.55	2.81	0.60	1.96	1.95	0.66	3.12	4.43	3.93	0.33	6.68	2.38	2.60	2.04	3.86	0.00	0.80	
FM		3.56	2.08	2.46	4.25	4.56	1.83	2.64	2.64	1.16	2.83	3.80	4.40	0.63	7.40	4.29	2.79	2.03	1.87	0.64	1.01	
SBM		2.85	0.92	1.63	2.95	2.27	0.44	1.99	1.51	0.39	1.72	1.90	4.63	0.38	8.14	1.73	2.21	2.07	1.42	0.17	0.74	

IAA, Indispensable amino acids; DAA, dispensable amino acids; HI, *Hermetia illucens*; TM, *Tenebrio molitor*; MD, *Musca domestica*; AD, *Acheta domestica*; ZM, *Zophobas morio*; FM, fish meal; SBM, soya bean meal.

Fish meal and soya bean meal are presented as average values from different authors. Fish meal was extracted from Abimorad et al. (2008); Djissou et al. (2016); Hall et al. (2018); Wang et al. (2005); Xie et al. (2016). Soya bean meal was extracted from Abimorad et al. (2008); Da et al. (2013); Djissou et al. (2016); Xie et al. (2016).

Table 4 Amino acids' apparent digestibility coefficient in *Oncorhynchus mykiss* (OM); *Dicentrarchus labrax* (DL); *Salmo salar* (SS); and *Claria gariepinus* (CG) fed with *Hermetia illucens* (HI) and *Gryllus bimaculatus* (GB)

Insect spp	Fish spp	Initial weight (g)	% inclusion	Arg	His	Iso	Leu	Lys	Met	Phe	Thr	Trp	Val	Ala	Asp	Cys	Glu	Gly	Pro	Ser	Tau	Tyr	Authors		
HI	OM	46.7	20	91.0	91.0	90.0	90.0	92.0	90.0	91.0	88.0	93.0				87.0					70.0		Dumas et al. (2018)		
HI	oil		20	93.0	92.0	92.0	91.0	93.0	92.0	92.0	90.0	95.0				88.0					77.0				
HI	DL	50.0	6.5	95.9	90.8	87.7	91.7	94.2	93.4	91.0	90.6		96.4	82.7	97.1	90.3	98.5	92.3	95.9	84.2	94.7	90.6	90.6	Magalhães et al.(2017)	
HI	DL		13	94.8	95.8	87.5	88.0	94.9	93.0	92.1	92.9		90.2	83.2	97.1	88.0	97.3	89.6	94.9	84.3	93.9	92.9	93.1		
HI	DL		19.5	96.7	98.1	88.5	81.5	93.6	93.3	93.6	93.1		91.9	76.7	97.0	91.1	98.2	87.6	94.8	83.4	95.8				
HI	SS	246.5	25	93.7	89.2	91.4	91.7	91.7	91.7	91.8	84.0		90.0	88.9	77.7		94.3	83.3	92.0	88.9		90.6	90.6	Lock et al. (2016)	
HI	SS		50	94.2	91.2	91.8	92.7	92.5	92.7	93.1	86.5		91.4	90.6	79.7		95.2	83.8	93.8	89.7		93.3			
HI	SS		100	93.8	90.6	90.5	91.9	91.4	91.9	93.3	84.9		90.5	90.4	78.4		93.9	83.6	92.7	89.6		93.5			
HI	SS		25	93.6	89.0	90.5	91.4	91.4	92.3	93.6	85.4		89.2	88.4	80.5		95.0	82.6	92.7	89.7		91.2			
HI	SS		100	92.5	89.4	89.9	90.8	91.6	91.5	91.6	83.0		90.3	90.6	79.7		93.5	84.2	91.8	87.6		91.3			
GB	CG	51.7	100	96.0	93.0	94.3	93.9	96.1	90.0	92.6	91.7	95.2	93.9									92.2	92.2	Taufek et al. (2016)	
HI	SS	48.5	12	98.1		97.9	98.0	97.9			96.9		97.6	97.6	94.2		98.2	96.1	98.0	97.2				Beight et al. (2018)	
HI	oil ⁻¹																								
HI	SS		12	98.1		98.0	98.1	98.1			97.1		97.9	97.9	94.9		95.5	96.3	98.1	97.3					
HI	oil ⁻²																								
HI	SS		85	97.5	96.0	96.8	97.1	96.5		97.2	95.5		96.7	96.5	95.4		97.2	94.8	97.2	96.0			97.2		
HI+oil ¹	SS		85 + 12	97.4	96.0	96.7	97.0	96.6		97.1	95.8		96.8	96.5	95.6		97.2	94.7	97.2	96.1			97.3		
HI+oil ²	SS		85 + 12	97.4	96.3	96.9	97.0	96.5		97.3	95.8		96.8	96.1	95.5		97.2	94.8	97.5	96.3			97.5		

cod, whose requirements are fixed at 2.62 g kg⁻¹ (Grisdale-Helland *et al.* 2011), and Nguyen and Davis (2016) obtained the best growth performance in catfish and Nile tilapia at 1.91% and 1.81%, respectively. Moreover, the digestibility values reported for Lys ranged from 91.4% in *S. salar* fed with 25% and 100% HI meal to 98.1% in *S. salar* fed with a 12% HI oil (Table 4).

Methionine

In addition to lysine, the IAA methionine (Met) is one of the most limiting amino acids in raw material designated for fish nutrition. In insect meals, the Met content ranged from 0.59 to 4.03 g 100 g⁻¹ sample, and these values were much higher than those obtained in SBM (0.44 g 100 g⁻¹), but only MD exhibited values similar to those found in FM (Table 3). Moreover, it appears that almost all insect meals could cover the requirements of omnivorous fish species, such as common carp larvae, which have requirements fixed at 0.61% (Wu *et al.* 2017). In the case of carnivorous fish, such as *Psetta maxima*, it would be necessary to supplement certain insect meals with Met to cover the demands of this species, which are stabilized between 1.49% and 1.59% (Ma *et al.* 2013). Only a few authors have determined the digestibility of Met, and the range of digestibility fluctuated from 90% in *Clarias gariepinus* fed with *Gryllus bimaculatus* to 93.4% in *D. labrax* fed with 6.5% HI meal (Table 4).

Phenylalanine

The content of phenylalanine (Phe) in insect meals fluctuates between 1.32 and 3.85 g 100 g⁻¹ sample (Table 3), and MD meal was the only type that exhibited values that were similar to higher than those observed in FM. Nevertheless, it seems that all of these insect meals could cover the requirements for common carp larvae, which are fixed at 1.09%, but better muscular growth could be achieved with a diet with 1.39% Phe (Yamashiro *et al.* 2016). In addition, the digestibility of this IAA ranged from 91% in both *O. mykiss* fed with 20% HI meal (Dumas *et al.* 2018) and *D. labrax* fed with 6.5% HI meal to 97.3% in *S. salar* fed with a combination of HI meal and oil (Belghit *et al.* 2018).

Threonine

The values in Table 3 indicate that the content of threonine (Thr) in insect meals is between 0.88 and 3.32 g 100 g⁻¹ sample, and both of these values were found in MD meal (Table 4). Although none of the insect meals reached the average value of FM (2.64 g 100 g⁻¹ sample), most of them had values that were higher than those in SBM

(1.51 g 100 g⁻¹ sample). In addition, these five insect meals can cover the demands of some species such as carp, which are fixed at 1.37% (Gao *et al.* 2014) and 1.48% (Zehra & Khan 2016) and 1.31% for Atlantic salmon (Helland & Grisdale-Helland 2011). The digestibility values for Thr vary, and the lowest value was 83% in *S. salar* fed with 100% HI meal, and the highest value was observed in *S. salar* fed with HI oil (Table 5).

Tryptophan

As shown in Table 3, the Tryptophan (Trp) values ranged from 0.39 g 100 g⁻¹ sample in TM larvae to 4.10 g 100 g⁻¹ sample in MD larvae meal, and these values were much higher than those reported for FM (1.16 g 100 g⁻¹ sample). All insect meals except the previously mentioned type exhibited values that were higher than those observed in SBM (0.39 g 100 g⁻¹ sample). However, the values in all insect meals could be sufficient to cover the requirements of catfish, which are fixed at 2.5–3.4 g kg⁻¹. Reductions in this amino acid cause reduced growth and altered enzymatic and metabolic processes (Pianesso *et al.* 2015). The Trp digestibility was reported by only two authors. Dumas *et al.* (2018) commented that HI meal reduced the digestibility of Trp by 93% in comparison with that observed in HI oil (95%) in *O. mykiss*, and Taufek *et al.* (2016) found that *C. gariepinus* fed with *G. bimaculatus* meal obtained a 95.2% digestibility of this IAA (Table 4).

Valine

The content of valine (Val) in insect meals varies from 1.91 g 100 g⁻¹ sample in MD larvae to 5.02 g 100 g⁻¹ sample in MD pupae (Table 3). Most of the insect meals had values that were similar to those observed in FM (2.83 g 100 g⁻¹ sample), but these values were significantly higher than those observed in SBM (1.72 g 100 g⁻¹ sample). These values seem to be high enough to cover the demands of fish such as *Paralichthys olivaceus* (Han *et al.* 2014), or they are much higher than the requirement of fish such as *Pagrus major*, which has an estimated level of 0.9% (Rahimnejad & Lee 2013). The digestibility of Val fluctuated from 89.2% in *S. salar* fed with 25% HI meal (Lock *et al.* 2016), and the highest value was also obtained with *S. salar* fed with 12% HI oil (Taufek *et al.* 2016).

Dispensable amino acids

Alanine

There was great variability in alanine (Ala) in insect meals, from 1.57 g 100 g⁻¹ sample in MD larvae meal to 7.14 g 100 g⁻¹ sample in AD nymph meal (Table 3). Most of the insect meals in Table 3, such as AD, ZM, TM and HI

Table 5 The amino acid scores of insect meals, SBM and FM in different fish species

Fish species	<i>Hermetia illucens</i>	<i>Musca domestica</i>	<i>Tenebrio molitor</i>	<i>Acheta domesticus</i>	<i>Zophobas morio</i>	Soybean meal	Fish meal
<i>Salmo salar</i>	Met+Cys (89.22)	RC	RC	RC	Met+Cys (83.16)	Met+Cys (98.80)	RC
<i>Oncorhynchus mykiss</i>	RC	RC	RC	RC	RC	Trp (66.21)	RC
<i>Sparus aurata</i>	Met+Cys (69.14)	RC	RC	RC	Met+Cys (64.45)	Trp (55.18)	Met+Cys (92.48)
<i>Acipenser transmontanus</i>	RC	RC	RC	RC	RC	RC	RC
<i>Cyprinus carpio</i>	Met+Cys (89.22)	RC	RC	RC	Met+Cys (83.16)	Trp (41.38)	RC
<i>Pagrus major</i>	RC	RC	RC	RC	RC	Trp (55.18)	RC
<i>Oreochromis niloticus</i>	Met+Cys (86.43)	RC	RC	Trp (86.10)	Met+Cys (80.56)	Trp (33.11)	RC
<i>Ictalurus punctatus</i>	RC	RC	RC	RC	RC	Trp (66.10)	RC
<i>Prochilodus lineatus</i>	RC	RC	RC	RC	RC	Trp (49.51)	RC
<i>Brycon amazonicus</i>	RC	RC	RC	Trp (84.41)	RC	Trp (32.46)	RC
<i>Chanos chanos</i>	Met+Cys (89.22)	Thr (99.05)	RC	Thr (89.10)	Thr (95.48)	Trp (55.18)	RC
<i>Dicentrarchus labrax</i>	RC	RC	RC	RC	RC	Trp (55.18)	RC
<i>Scophthalmus maximus</i>	RC	RC	RC	RC	Met+Cys (95.48)	Trp (55.18)	RC

RC, Requirement covered.

Insect meals: Bosch *et al.* (2014); Finke (2002); Finke (2007); Finke (2012); Finke (2015); Ghaly and Alkoaik (2009); Hopley (2016); Janssen *et al.* (2017); Sánchez-Muros *et al.* (2016). Fish meal: Aas *et al.* (2006); Martínez-Llorens *et al.* (2012); Nogales-Mérida *et al.* (2017); Sogbesan & Ugwumba, (2008); Wilson *et al.* (1980). Soybean meal: Wilson *et al.* (1980). Fish body composition: Aas *et al.* (2006); Aas *et al.* (2007); Akiyama *et al.* (1997); Sánchez-Lozano *et al.* (2010).

larvae meal and MD pupae meals, exhibited similar and even higher levels than those found in FM (3.80 g 100 g⁻¹ sample), and these levels were much higher than those found in SBM (1.90 g 100 g⁻¹ sample). Ala is perhaps one of the attractants for the consumption of insects by fish in the wild. In addition, the digestibility of this DAA fluctuated from 76.7% in *D. labrax* fed with 20% HI meal, and the highest value was obtained in *S. salar* (97.6%) fed with 12% HI oil (Table 4).

Aspartic acid

The content of Aspartic acid (Asp) in insect meals also widely varied, especially in one species in which the content varied from 0.64 g 100 g⁻¹ sample in MD larvae to 6.47 g 100 g⁻¹ sample in MD pupae. The remaining insect meals exhibited values that were similar to those found in FM and SBM (Table 3). Considering these facts, we expect that insect meals could cover the Asp demands of fish and prevent stress, as done by Trp, as found by Gonzales-Silvera *et al.* (2018) in *Argyrosomus regius* fed with aspartate. Moreover, the digestibility of Asp ranged from 77.7% in *S. salar* fed with 25% HI meal, and the highest value was found in *D. labrax* fed with 6.5–13% HI meal (Table 4).

Cysteine

The proportion of cysteine (Cys) in insect meals ranged between 0.01 g 100 g⁻¹ sample in HI larvae meal and 1.74 g 100 g⁻¹ sample in MD larvae meal (Table 3). In this DAA, great variability was also found among the insect meals, and this variation was most likely due to the farming conditions and the type of feed received. Schiavone *et al.* (2017) reported the lowest Cys values in HI larvae meal, and Pieterse and Pretorius (2014) reported the lowest values in MD larvae meal. These values are too low if they are compared with the values in the rest of the reported insect meals. If the values that were reported to cover fish demands are correct, it would be necessary to supplement the fish diets with Cys because Zehra and Khan (2016) affirmed that 0.51% of Cys could cover the demands of *Catla catla* fingerlings. In addition, if we consider that 1% of additional Cys can prevent mercury contamination in fish (Mok *et al.* 2014), the use of MD and TM larvae fed cereal by-products (De Marco *et al.* 2015; Iaconisi *et al.* 2017) could be an option to improve the Cys contents in the meal. However, the highest value was observed in MD larvae fed chicken manure (Hall *et al.* 2018). The digestibility of Cys was reported by only two

authors, and the values ranged from 87% to 91.1% (Table 4).

Glutamic acid

The presence of glutamic acid (Glu) in insect meals ranged from 0.00 g 100 g⁻¹ sample (Pieterse & Pretorius 2014) to 8.44 g 100 g⁻¹ sample, and both of these values were observed in MD (Table 3). Pieterse and Pretorius (2014) also reported a low value for MD pupae (1.40 g 100 g⁻¹ sample). In general, the levels of this DAA were lower in the insect meals than those observed in FM and SBM, but this can be compensated by the higher amount of Arg in the insect meals. The digestibility of Glu ranged between 93.9% in *S. salar* fed with 100% HI meal to 98.5% in *D. labrax* fed with 6.5% HI meal (Table 4).

Glycine

The content of glycine in insects varies from 1.03 g 100 g⁻¹ sample in MD larvae to 5.68 g 100 g⁻¹ sample in TM larvae (Table 3). In general, all insect meals presented lower values than those observed in FM (4.29 g 100 g⁻¹ sample), but the values were higher than those observed in SBM (1.73 g 100 g⁻¹ sample). The digestibility values in Gly fluctuated from 82.6% in *S. salar* fed with 25% HI meal to 96.3% in the same species fed with 12% HI oil (Table 4).

Proline

The values of Pro in insect meals ranged from 1.56 g 100 g⁻¹ sample in MD larvae to 5.55 g 100 g⁻¹ sample in HI larvae (Table 3). The content of Pro in insect meal was predominantly higher than that in FM and SBM. The lowest digestibility values were obtained in *S. salar* fed with 25% HI meal (92.0%), and the highest digestibility value of 98.1% was observed in the same species 12% of HI oil inclusion (Table 4).

Serine

The serine content in insect meals was between 0.91 g 100 g⁻¹ sample in MD larvae and 2.79 g 100 g⁻¹ sample in AD nymphs (Table 3). Generally, these values were similar to those observed in FM and SBM. In addition, the lowest digestibility value was obtained in *D. labrax* fed with 20% HI meal (83.4%), and the highest value was observed in *S. salar* fed with HI oil (97.3%).

Taurine

Most of the authors consulted did not determine the Tau content in the insect meal samples, but did report values

from 0.003 g 100 g⁻¹ sample for TM adults and ZM larvae to 4.58 g 100 g⁻¹ sample for AD adults. Only Dumas *et al.* (2018) and Magalhães *et al.* (2017) reported the digestibility of Tau in *O. mykiss* and *D. labrax*, respectively. Both fish species were fed with HI, but the first authors reported the lowest digestibility values (70% and 77%), and the digestibility values reported by the second authors ranged from 93.9% to 95.8% (Table 4).

Tyrosine

The proportion of tyrosine (Tyr) in insect meals fluctuates from 0.77 g 100 g⁻¹ sample in AD nymphs and HI larvae to 1.90 g 100 g⁻¹ sample in MD pupae (Table 3). The insect meals have lower values than those in FM but higher values than those in SBM. The digestibility values fluctuated from 91.2% in *S. salar* fed with 25% HI meal, and the highest values were found in the same species fed with HI meal and HI oil (97.5%).

The relationship between the AAs present in insect meals and their digestibility were compared: there are many aspects that caused these variations that seem to be related to the growth stage of the fish. The type of food proportionate to the insects and the stage of development will have a direct effect on the quality of insect meal, which will affect the digestibility of the fish target.

IAA/DAA ratio

The IAA/DAA ratio is a valuable tool used to determine whether the amino acid profile of a raw meal provides the correct balance between IAAs and DAAs. When a meal has a ratio close to 1.0, the meal is considered balanced, but when the value is less than 1.0, as is the case for SBM (0.83), the ratio indicates an imbalance, which can be corrected by the addition of synthetic amino acids or the mixture with other raw meals that contain a proportionate number of missing amino acids. Insect meals have ratios between 0.78 and 1.12 (Table 3). The value for FM was 1.01, and the value for SBM was 0.74, which is the lowest value of all meals.

Indispensable amino acid score

The amino acid score is a mathematical method used to predict the nutritional value of feed ingredients (Hardy & Barrows 2002) that is based on a comparison of the concentration of the first limiting essential amino acid in the test protein with the concentration of that amino acid in a reference (scoring) pattern. When comparing the AA scores of the different insect meals fed to finfish in general, only ZM contained a low Met+Cys score (98.48),

but in comparison with SBM, the lowest score was found in Trp (51.00). The other insect meals and FM have high scores in all IAAs. To determine the amino acid score, the work of different authors was used because they referred to the amino acid values in $\text{g } 100 \text{ g}^{-1}$ of CP (Fig. 1).

The chemical score formula used in this manuscript was proposed by Hardy and Barrows (2002):

$$\text{Chemical Score} = \left\{ \frac{\text{mg limiting AA in test protein}}{\text{mg AA in reference protein}} \right\} \times 100$$

Although the highest Met content values were found in insect meals ($\text{g } 100 \text{ g}^{-1}$ CP), the values used to determine the IAA score indicated that insect meals show deficiencies for different fish species. The ZM meal is deficient in Met+Cys for Atlantic salmon (*S. salar*), Gilthead seabream *Sparus aurata*, common carp (*Ciprinus carpio*), Nile tilapia (*Oreochromis niloticus*) and turbot (*Scophthalmus maximus*) and has the lowest score in Thr for milkfish (*Chanos chanos*). Additionally, HI has the lowest Met+Cys score for *S. salar*, *S. aurata*, *C. carpio*, *O. niloticus* and *C. chanos*, as shown in Table 5. However, the TM meal does not have a score below 100 for any of the compared fish species.

The AD meal does not meet the Trp requirements for *O. niloticus*, *Brycon amazonicus* or *C. chanos*. Additionally, MD is the other insect meal that shows deficiency but for only Thr content in *C. chanos*. Nevertheless, all scores obtained from the insect meals indicate that their deficiencies are not as severe as the deficiency of SBM in Trp, which fluctuates from 33.11 to 66.21. Even FM does not meet the requirements of *S. aurata* for Met+Cys, perhaps because in nature, this fish species mainly consumes gastropods and bivalves (Pita *et al.* 2002). Bosch *et al.* (2014) observed similar results and indicated that Met+Cys were the most limiting AAs for most insect meals designated for cat and dog nutrition. Additionally, Siriamornpun and Thammapat (2008) compared the IAAs of insects used in human nutrition and commented that *Modicogryllus confirmatus*, *Melanoplus ponderosus*, *Omphisa fuscidentalis* and *Holotrichia* sp. were deficient in Thr.

Antagonism in amino acids

Dietary imbalances may develop from disproportionate levels of specific amino acids that react as antagonists (Harper 1956 commented by Park 2006). Such an imbalance causes reductions in feed intake, growth depression and health problems and is more evident in young animals than in adults (Park 2006). A few antagonism cases have been observed: (i) arginine–lysine imbalances have been found

in meat bone meal, SBM and pea meal; (ii) a cysteine–methionine imbalance has been observed in blood meal (Tacon 1992); (iii) a leucine–isoleucine imbalance causes growth suppression (D'Mello 2003), and this imbalance was observed in TM meal, which could have affected African catfish fed with mealworm at an inclusion that was higher than 40% of substitution (Ng *et al.* 2001); however, in *Poecilia reticulata* fed dried insects, the best growth performance was obtained with larvae of *Dynastes hercules*, *Phlebotomus* and TM (Adil *et al.* 2014); and (iv) in a leucine–valine sp. imbalance, excess dietary leucine depresses plasma valine concentrations, but the opposite was not observed. Additionally, valine deficiency suppresses chick growth (D'Mello 2003), but valine deficiency in fish has not been studied.

Chitin

In general, insect chitin is primarily considered fibre because of its similar structure to cellulose. The exoskeleton of arthropods (cuticle) is built primarily of chitin fibres, and chitin is a polysaccharide of glucosamine and *N*-acetylglucosamine, which both contain nitrogen atoms. Because of the strong linkage of proteins in chitin fibres and changes in chitin according to life stage, estimations of the amounts of chitin and nondigestible protein in insect cuticles are variable: hard cuticles have high protein contents between 70% and 85% (dry weight) and low chitin contents of 15–30%, whereas soft cuticles contain approximately 50% each of chitin and proteins (Chapman 2013; Jonas-Levi & Martinez 2017).

In aquatic insects, the protein content inside the cuticle of the body can be as high as 11.6–13.72% or between 2.9% and 10.1% on a dry weight basis. These cuticular proteins are composed of AAs and chitinase-like proteins (Finke 2007; Arakane & Muthukrishnan 2009).

According to Finke (2007), the digestibility of proteins/AAs in insects can vary and depends on how much of the AAs are bound to chitin or scleroprotein that is mainly present in adult insect cuticles (Becker & Yu 2013). However, these proteins or amino acids can be available for fish nutrition because of chitinolytic activity from enzymes such as chitinase in the stomach and chitinase in the intestine (Lindsay 1983), which are present in the gastrointestinal tracts of many fish species that have 'natural diets' including shrimp, crabs, crayfish and insects (Lindsay & Gooday 1985; Gutowska *et al.* 2004). These chitinase activities were responsible for the reduction in *Escherichia coli* and caecal *Salmonella* sp. and the increase in *Lactobacillus* in broilers fed with chitin from shrimp meal (Khempaka sp. *et al.* 2011). In sea bass fed with different levels of chitin (0, 0.5, 1, 2, 3 and 4 g kg^{-1}), the growth and feed efficiency performance

improved up to 2 g kg⁻¹ of chitin. Simultaneously, the benefits of chitin in sea bass fingerling diets showed an increase in the length of the *villus* and *microvillus* in the intestine (Zaki *et al.* 2015). However, the amount of chitin in the diet must be considered because excessive chitin content can cause weight gain, as noted by Sánchez-Muros *et al.* (2016).

Bioactive forms of insect protein in antimicrobial peptides

Insect proteins are also a source of antimicrobial peptides that are biologically active fractions of insect proteins with activity against pathogenic bacteria (Józefiak & Engberg 2017). In addition to their antimicrobial effect, these peptides boost specific innate immune responses and exert selective immunomodulatory effects.

Currently, more than 1500 proteins with antimicrobial activity have been identified in different organisms, such as plants, fungi, bacteria and animals; however, most are in insects (Bulet *et al.* 1999; Yi *et al.* 2014). Moreover, their activity is widely recognized to not lead to the development of natural bacterial resistance or at least the frequency of resistance is considered to be low (Narayanan *et al.* 2014; Chernysh *et al.* 2015). According to the review of Józefiak and Engberg (2017), insect proteins could be a promising source of antimicrobial peptides and considered an alternative to antibiotics in veterinary and livestock production.

Fatty acids in insect meals

In insects as well as other animals, the type of fatty acid will reflect the type of food that is consumed by animals. However, the stage of development will affect the amount of lipids, as found by Pearincott (1960) in *M. domestica* larvae and pupae, and the conditions of rearing, as is shown in Table 2. These aspects will all affect the amount of fatty acids as well as their type (Table 6). The types of FA shown in this table are presented according to the importance that they have in fish nutrition, and the most abundant types in insect meals are studied in this manuscript.

Lauric acid (12:0)

This fatty acid is more abundant in HI than in the other meal types, and its abundance seemed to be conditionate on the type of feed, not the stage of development, as concluded by Spranghers *et al.* (2017) and shown in Table 6. It seems that MD lacks this FA, or the authors did not detect it. In the rest of the insect meals, the

values ranged from 0.007% to 1.00%, but the reported values ranged from 0.00% to 1.00%.

Myristic acid (14:0)

This FA was present in all insect meals, and HI again presented the highest content (5.10% to 9.4%). The second highest abundance was observed in MD, with values ranging from 2.70% to 6.8%. For the rest of the insect meals, their contents varied from 0.30% to 4.45%. The values of this FA were compared, and only MD exhibited values that were similar to those found in fish oil (FO; 5.73%), although the contents of myristic acid in all insect meals were much higher than those measured in soya bean oil (SBO; 0.10%).

Palmitic acid (16:0)

This FA is more abundant in insect meals than FO and SBO, and the content varied according to the insect species. This FA fluctuated from 21.40% to 38.01% in MD, from 22.65% to 25.99% in AD from 0.36% to 30.2% in ZM, from 6.0% to 23.6% in TM and from 8.70% to 19.80% in HI. In general, those values were much higher than those measured in FO (13.05%) and SBO (10.49%).

Stearic acid (18:0)

The values of stearic acid in insect meals varied from 1.1% to 8.80%, and the insect meals with high values in comparison with the other meals, FO and SBO were AD and ZM.

Saturated fatty acids (SFA)

The average values of the insect meals were compared, which indicated that HI exhibited the highest amount (67.47%), followed by ZM (37.40%); AD had an average of 32.48%, MD had an average of 32.66%, and TM had an average of 23.18%, which was similar to that measured in FO (23.33%) and higher than that measured in SBO (14.56%).

Palmitoleic acid (16:1n-7)

The values of insect meals indicated that MD presented the highest value, ranging from 5.59% to 29.60% in comparison with the rest of the insect meals (TM, HI, AD and ZM), which exhibited low values ranging from 0.20% to 7.60%, but the average value for FO was 5.51%, and that for SBO was 0.09%.

Table 6 Fatty acids of five insect meals reported by different authors, data expressed in percentage

Spp	Stage	12:0	14:0	16:0	18:0	20:0	SFA	16:1n-7	18:1n-9	MUFA	18:2n-6	18:3n-3	20:4n-6	20:5n-3	22:6n-3	PUFA	n-3	n-6	n-3/n-6	Authors
HI	Prep.	23.60	5.10	19.80	6.50		55.00	6.30	22.70	29.00	6.80	0.00		0.10		6.90	0.10	6.80	0.01	Sealey et al. (2011)
HI		37.10	6.30	17.30	2.00		62.70	7.60	18.80	26.40	5.90	0.50		3.50	1.70	12.10	6.20	5.90	1.05	Sealey et al. (2011)
HI	Prep.	47.0	6.50	15.00	2.20		71.60		14.00	14.30	9.40	0.80	0.10	0.10	0.10	10.60	1.10	9.50	0.12	Kroeckel et al. (2012)
HI	Larva	36.37	6.25	14.71	2.37		59.7	2.01	16.13	19.8	19.33	0.15	0.25			19.73	0.15	19.58	0.01	Li et al. (2016)
HI	Prep.	57.35	7.34	9.65	1.36		77.13	1.97	7.54	9.51	11.55	0.70		0.60	0.10	13.45	1.90	11.55	0.16	Spranghers et al. (2017)
HI		43.65	6.87	10.12	1.75		63.56	7.58	7.93	15.51	7.90	0.83		0.11	0.20	9.69	1.79	7.90	0.23	(2017)
HI		60.89	9.48	8.70	1.11		81.81	2.93	5.66	8.59	4.52	1.37		0.01	0.01	6.78	2.26	4.52	0.50	
HI		57.56	7.14	10.29	0.98		78.00	3.34	7.97	11.43	7.83	1.10		0.23	0.01	9.67	1.84	7.83	0.23	
HI	Larva	52.60	8.54	10.9	1.53		75.00	1.98	6.16	8.14	11.6	1.01	0.29	0.00		12.90	1.01	11.89	0.08	Schiavone et al. (2017)
HI	Larva	40.60	8.50	14.80	2.50		66.40	2.00	8.80	10.80	17.90	1.40				19.30	1.40	17.90	0.08	Liland et al. (2017)
HI		23.90	6.70	16.60	4.10		51.30	2.50	17.90	20.40	18.60	1.60	2.10	1.00		23.3	2.60	20.70	0.13	Liland et al. (2017)
TM	Larva		1.50	23.60	1.40	1.50	28.00		44.70	44.70	24.10	1.50				25.60	1.50	24.10	0.06	Fast (1966)
TM	Larva		3.05	16.72	2.49		22.26	2.67	43.17	46.08	30.23	1.36				31.59	1.36	30.23	0.04	Ravzanaadli et al.
TM	Adult		1.84	18.65	6.17		26.66	2.20	36.74	39.51	32.46	0.74				33.81	0.74	32.62	0.02	(2012)
TM	Larva	0.23	3.11	18.52	2.43	0.00	24.29	2.79	49.72	52.51	21.82	0.84				22.66	0.84	21.82	0.04	Tzompa-Sosa et al.
TM		0.14	3.18	17.31	2.82	0.00	23.45	2.74	49.15	51.89	23.35	0.85				24.20	0.85	23.35	0.04	(2014)
TM		0.28	3.60	17.96			21.84	2.90	49.15	52.10	21.67	0.89				22.56	0.89	21.67	0.04	
TM	Larva		2.32	16.19	2.97		21.48	1.56	46.41	48.36	27.83	1.48				29.31	1.48	27.83	0.05	Van Broekhoven (2015)
TM		0.38	3.19	16.96	2.72		23.25	2.88	48.68	51.82	20.99	0.67				21.66	0.67	20.99	0.03	
TM			2.20	16.13	2.64	0.16	21.47	2.67	39.78	42.85	31.25	1.29		0.21	0.24	32.99	1.74	31.25	0.06	
TM			2.79	16.67			19.95	1.56	57.63	59.39	15.45					15.45	0.00	15.45	0.00	
TM	Larva	0.20	3.50	18.40	6.60	0.30	29.40		36.50	36.50	30.50	1.10	0.10			31.70	1.10	30.6	0.04	Adámková et al. (2016)
TM	Larva	0.21	0.36	17.77	3.23	0.18	21.76	1.41	39.712	41.357	29.90	1.74				31.63	1.739	29.89	0.06	Jeon et al. (2016)
TM	Larva	0.30	2.60	20.20	4.30	0.60	28.30	0.40	37.70	38.10	31.90	1.70				33.60	1.70	31.90	0.05	Adámková et al.
TM		0.20	2.50	21.30	4.80	0.70	29.70	0.20	36.30	36.05	31.90	1.80				33.70	1.80	31.90	0.06	(2017)
TM	Larva		4.45	21.33	7.92		33.7	1.97		1.97	22.83	0.11				22.94	0.11	22.83	0.00	Paul et al. (2017)
TM	Larva		0.90	6.00	1.10		8.00	0.60	12.80	13.40	8.80	0.40	0.04	0.04	0.04	9.32	0.48	8.84	0.05	Personal data
MD	Larva		5.11	21.40	2.63		29.14	17.5	33.10	50.6	16.80					16.80	0.00	16.80	0.00	Barlow (1966)
MD	Larva		2.12	21.40	2.63		26.15	24.20	49.00	73.20						0.00	0.00	0.00		
MD	Adult		6.80	22.80	4.50	1.30	35.40	24.00	29.30	53.30	3.30	1.30				4.60	1.30	3.30	0.39	Fast (1966)
MD	Larva		4.08	38.01	4.39	0.09		8.26	22.62		26.25	1.99	0.10	0.03	0.03	28.4	2.05	26.35	0.08	Pretorius (2011)
MD	Pupa		2.70	34.85	2.75	0.14	40.44	5.59	22.83	28.79	36.27	2.73	0.05	0.15	0.03	39.23	2.91	36.32	0.08	
MD	Larva		4.50	25.28	2.41		32.19	0.00	22.22	22.22	2.82	0.56	0.05			3.82	0.95	2.87	0.33	Hussein et al. (2017)
MD	Larva		3.10	21.4	4.20	7.50	36.20	29.60	26.60	56.20	7.30	7.50				14.8	7.30	7.50	0.97	Fast (1966)
AD	Adult	0.30	1.80	25.99	6.09	0.00	34.38	2.77	29.14	32.00	34.35	1.59		0.64		36.58	2.23	34.35	0.06	Tzompa-Sosa et al.
AD		0.16	1.55	23.69	6.76	0.09	32.36	2.38	26.63	29.01	31.8	1.74		0.46		34	2.20	31.80	0.07	(2014)
AD		0.27	1.65	24.81	4.61	0.00	31.34	2.79	30.23	33.02	31.8	1.74		0.75		34.29	2.49	31.80	0.08	
AD	Adult	0.10	0.44	22.65	8.54		31.85	0.34		0.34	41.39	1.11				42.5	1.11	41.39	0.03	Paul et al. (2017)

Table 6 (continued)

Spp	Stage	12:0	14:0	16:0	18:0	20:0	SFA	16:1n-7	18:1n-9	MUFA	18:2n-6	18:3n-3	20:4n-6	20:5n-3	22:6n-3	PUFA	n-3	n-6	n-3/n-6	Authors
ZM	Larva	0.007	0.17	0.36	1.15	0.03	5.03	0.137	4.28	4.435	2.64	0.376	0.01	0.03	0.01	3.075	0.43	2.65	0.16	Finke (2015)
ZM	Larva	1.00	1.70	30.20	8.80	0.20	43.00	0.70	0.10	32.00	21.20	0.90	0.10			22.20	0.90	21.30	0.04	Adámková <i>et al.</i> (2016)
ZM	Larva	0.70	1.40	29.10	6.40	0.10	37.90	1.20	35.70	36.90	23.40	1.60				25.00	1.60	23.40	0.07	Adámková <i>et al.</i> (2017)
ZM	Larva		0.30	10.10	3.00	0.10	13.70	0.20	9.90	10.10	7.90	0.30	0.04	0.04	0.04	8.32	0.38	7.94	0.05	Personal data
FO		3.80	5.73	13.05	2.98	0.17	23.32	5.51	14.47	19.33	2.35	0.62	1.07	9.87	10.24	19.14	16.19	2.84	8.30	Suseno <i>et al.</i> (2014), De Haro <i>et al.</i> (2016), Trushenski <i>et al.</i> (2015)
SBO			0.10	10.48	3.88	0.40	14.56	0.09	20.86	21.06	53.48	7.71				58.73	5.21	53.48	0.10	Deng <i>et al.</i> (2014), Liu <i>et al.</i> (2016), Nogales-Mérida <i>et al.</i> (2017)

HI, *Hermetia illucens*; TM, *Tenebrio molitor*; MD, *Musca domestica*; AD, *Acheta domestica*; ZM, *Zophobas morio*; FO, fish oil; SBO, soybean oil.

Oleic acid (18:1n-9)

Oleic acid is the most abundant monounsaturated fatty acid, especially in TM, with values ranging from 12.80% to 57.63%, which are the highest values; it was also abundant in MD (22.22% to 49.00%). The concentrations in *A. domestica* varied from 29.14% to 30.23%, and the contents in HI and ZM measured by different authors varied although the values of HI were similar to the values of FO (14.47%, Table 6).

Monounsaturated fatty acids

As a natural consequence of high monounsaturated fatty acid (MUFA) contents, TM exhibited the highest content ranging from 36.5% to 52.51%, and only Paul *et al.* (2017) and unpublished data exhibited values that were lower than those previously mentioned. *M. domestica* also exhibited higher values ranging from 22.22% to 73.20%, and the values of AD ranged from 29% to 33%. The values fluctuated from 8.10% to 29.00% in HI and 4.40% to 36.90% in ZM.

Polyunsaturated fatty acids

Linoleic acid (18:2n-6)

In general, insects are rich sources of linoleic acid (LA), and the species that exhibited the highest values were TM and AD. In these two species, the values were more constant than those observed in HI, MD and ZM. Generally, insect meals have a tendency to exhibit not only the fatty acids of their diets but also the characteristics of each species, as found by Van Broekhoven (2015), and this is more evident in the cases of TM, MD and AD. In addition, the values of insect meals were more related to the abundance of SBO than the abundance of FO.

Linolenic acid (18:3n-3)

This polyunsaturated fatty acid (PUFA) is one of the most important fatty acids in continental fish because of its capacity to bioconvert into HUFAs. The values found in insect meals are not as high as those observed in SBO or other plant oils. The content of this PUFA varies from 0.00% to 2.73%, and the highest values were more abundant in MD than those in the other insect meals.

Arachidonic acid (20:4n6)

The arachidonic acid (ARA) values were limited in insect meals, except in HI larvae meal (2.1%) fed with seaweed-enriched media (Liland *et al.* 2017); this value was even higher than the average value of FM (1.07%). The rest of

the insect meals exhibited values from 0.01% to 0.29% in the best of the cases (Table 6).

Eicosapentaenoic acid (20:5n-3)

As indicated by Liland *et al.* (2017), HI seems to have the capacity to modify its FA profile according to the diet, as shown in Table 6; HI more frequently exhibited the presence of this PUFA with values ranging from 0.01% to 3.50%. The next most frequent presence was detected in AD, which exhibited values from 0.46% to 0.75%. Some authors have shown the presence of eicosapentaenoic acid (EPA) in various compositions, but this presence is not as frequent as observed in HI and AD. However, the values obtained in insect meals are much lower than those found in FO (9.87%) but higher than those in SBO.

Docosahexaenoic acid (22:6n-3)

HI again more frequently presented the docosahexaenoic acid (DHA) FA in comparison with the rest of the insect meals, and the values ranged from 0.01% to 1.70%, which were obtained in larvae fed with manure and fish offal (Sealey *et al.* 2011). The presence of DHA was more scarce than the presence of EPA in the insect meals, and the presence in the rest of the meals ranged from 0.01% to 0.24%. Again, the values were much higher in FO than in the other meals, but as we can observe, SBO completely lacked DHA as well as EPA.

Polyunsaturated fatty acids

In insect meals, the contents of PUFAs mainly reflected LA; for instance, TM and AD exhibited the highest values, while the values of MD, HI and ZM fluctuated according to the content of LA.

Omega 3 (ω 3)

The sum of these fatty acids was very low, fluctuating from 0% to 7.2%, but the highest values were observed in MD, which contained only linolenic acid (LNA), and the second highest value (6.2%) was found in HI fed with algae meal (Sealey *et al.* 2011). The remaining insect meals reached 2.91%, and these values were low in comparison with those measured in FM (16.19%) and SBO (5.21%).

Omega 6 (ω 6)

The sum of ω 6 fluctuated from 3.3% to 36.32%, and these values were much higher than those reported for FO but lower than those for SBO.

Relation omega 3/omega 6

The relationship between ω 3/ ω 6 was very low; only HI prepupae obtained the highest value (1.05%), and the rest of the insect meals fluctuated from 0% to 0.50%. These values were too low, which would represent a problem if FO was completely replaced with any insect meal. It is necessary to conduct more trials to determine an adequate feed to improve the omega 3 content in insect meals, especially in HI, which seems to adapt more easily to new diets, as tested by Sealey *et al.* (2011) and Liland *et al.* (2017).

We can also observe that in the case of fatty acids, the type of extraction affects the type of fatty acid that will be reflected in the analysis, as shown by Tzompa-Sosa *et al.* (2014) in AD meal.

Sensory quality of insect meals

Palatability of insects is also an important factor that determines whether an insect can be used as feed. As part of the natural fish diet, insects have the 'natural attractant' component. However, fish, like other animals, can reject a feed based on insect meal because of an unpalatable flavour, bitterness, sourness or odour, among other factors. Sometimes, these unpleasant flavours, such as bitterness or sourness, can hide toxins and/or contaminants that cause immediate rejection of a food source (Reed & Knaapila 2010). In other cases, these unpleasant flavours may be related to the process of insect meal elaboration, such as drying or freezing, which can affect the quality and palatability of the insect meal. The Maillard reaction is associated with this aspect, which can occur during the drying process of insect meal and can improve or have adverse effects on the meal process and affect the palatability (Tamanna & Mahmood 2015). In contrast, the flavour is primarily affected by pheromones occurring on the surface of insects (Ramos-Elorduy 1998). Flavour also depends on the environment in which the insects live and the feed that is consumed (Kouřimská & Adámková 2016). For European sea bass fed with *H. illucens* prepupae meal, palatability was not a problem because no differences were detected in the amount of feed consumed by the fish (Magalhães *et al.* 2017). To ensure insect meal palatability, defatting and drying processing methods may be an option, as demonstrated by Fasakin *et al.* (2003) in catfish fed with defatted and full-fat maggot meal. No studies have related insect meal palatability to fish nutrition, although this important point is one in which insect farming could play a crucial role in obtaining insect meal of high quality and palatability.

Processing of insect meals

Another crucial point is the different ways of processing the insect meals that will have a direct effect on the growth performance and feed efficiency. For example, *S. salar* fed with two types of BSF meals were submitted to different nutrient isolation and processing techniques, which affected the growth performance and feed efficiency at the end of the experiment (Lock *et al.* 2016). As in plant meals, insect meals will soon begin to offer not only the entire animal meal but also other derivate products such as protein concentrates, chitins, oils, antimicrobial peptides, and all of these products are destined not only to improve growth performance but also to increase fish immunity, as only insects can provide.

Conclusions and perspectives

Insect meals are one of the best alternatives to partially or completely replace fish meal, which is mainly due to the versatility and ability of insects to change their amino acid and fatty acid profiles. Moreover, insects are natural food sources for fish, especially continental species. All these aspects promote the use of insects in fish nutrition, but it is necessary to consider that in nature, fish eat not only one insect species but also many at the same time, and the consumption of insects by fish can vary seasonally. To improve the use of insects, we should consider working not only with one insect species but also with many at the same time to enhance the diet quality. It is necessary to determine the stages when fish consume more insects in nature.

We should consider using insects not only as meal replacements but also as probiotics due to the presence of both chitin and AMPs in insects. Therefore, the inclusion of insect meal in fish diets at even relatively low quantities could improve the immune systems of fish and promote their performance, as previously shown in other livestock species. However, we must remember that more than 200 species of fish are farmed, and the dietary requirements of these species are not well known. It is not possible to determine the response of one species and consider all of the possible effects on other species; however, the process of insect meal elaboration before use in animal feeds should be considered. Additionally, the Maillard effects on protein quality and the quantity of an insect meal should be considered when determining a target fish diet.

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