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Use of insect products in pig diets

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REVIEW ARTICLE

Abstract

This review is focusing on effects of inclusion of insect products in pig diets on digestibility, performance, product quality, and health parameters. In 2019 pig feed accounts for 23% of the global feed production. Soybean meal is the most common protein source in pig diets. A shift towards more sustainable feed ingredients can improve the sustainability of entire pig production. Novel protein sources currently evaluated in diets for piglets and growing pigs are insect-based ingredients. Insects are able to convert organic biomass into high-quality protein. Currently the use of insects as protein source in pig diets is not allowed due to transmissible spongiform encephalopathies regulation but it is expected that this will be allowed in the near future. Research efforts on effects of inclusion of insect products on nutrient digestibility, growth performance, product quality and pig health are therefore increasing. Nutrient digestibility of evaluated insect proteins was comparable with traditional protein sources. Nutrient digestibility of insect-based diets as well as effects on growth performance in pigs fed insect-based diets differed between studies. The differences in responses are mainly due to changes in diet ingredients and nutrient composition when insect products are included. Health related parameters were not affected by dietary inclusion of insect products. In general it can be stated that differences in results between studies may be due to different insect species and life stages being used, differences in nutritional value of the insect products, in dietary inclusion levels, in processing techniques applied, effects on palatability of the diet, (weaning) age of the animals involved and research methods applied. Overall, insect products seem to be a good alternative to partly replace traditional protein-rich ingredients in pig diets without adversely affecting growth performance, product quality and health, but more standardised research is required to reduce differences between studies.

Keywords: insect protein, feed, pigs, digestibility and growth performance, animal health

1. Introduction

This review is focusing on effects of inclusion of insect products in pig diets on nutrient digestibility of the diet, animal performance, product quality, and health parameters. The review starts with a general description of the development of pig production in the past and expected developments in the future as well as sustainability aspects in pig production mainly focussing on pig nutrition and possibilities on how to create more sustainable pig diets by use of insect-based feed ingredients. The chemical compositions of different insect species are presented and compared to the chemical composition of traditional protein sources such as soybean meal and fishmeal. The chemical composition of insect protein is important to put the effect of nutrient digestibility of insect proteins on the overall nutritional value in perspective. Only relevant papers for evaluation of nutrient digestibility, growth performance, product quality, and health parameters, published since 2000, were considered. For studies on effects of inclusion of insect products as feed ingredient in pig diets on growth performance only papers were included which met the criteria of isonitrogenously and isocalorically formulated diets. This was done to ensure that outcome parameters can be solely attributed to the inclusion of insect-based feed ingredients in the diet and not to differences in protein levels or energy levels.

2. Global meat consumption and pig production

In the past 50 years, global pig production has quadrupled and is expected to continue to grow in the next three decades. This may have a significant impact on feed use and land demand (Lassaletta *et al.*, 2019). The growing demand for pig meat results from the increase in population, as well as from the transition of the diet towards more animal protein consumption per capita (Bai *et al.*, 2018; Lassaletta *et al.*, 2014). Globally, meat consumption is generally influenced by a number of factors, such as food consumption patterns, the standard of living, meat production and animal husbandry conditions and product pricing. Also many consumers will change their eating habits, including consumption of more animal protein when urbanisation intensifies (Soare and Chiurciu, 2017). Although in Western Europe the consumption of meat is not expected to increase much (De Boer *et al.*, 2006), it has been forecasted that the worldwide demand for animal products will grow significantly in the coming decades, and that the global production of meat will double in 2050 taking 1999 as the base year (Steinfeld *et al.*, 2006). Globally, 767.5 billion pigs were produced in 2019 (USDA, 2020). Global feed production is estimated at 1,126 million metric tons in 2019 (Alltech, 2020). The production of pig feed in 2019 is estimated to be 261 million metric tons, accounting for 23.2% of the total global feed production. In 2019, pig feed production in Europe was 79.5 million metric tons, accounting for 30% of the total pig feed production (Alltech, 2020). The expected increase of global population and consumption of pig meat will require a higher demand for pig feed in the future.

3. Sustainability aspects of pig diets

Meat consumption contributes to the supply of energy, protein, essential amino acids and important micronutrients (e.g. long-chain n-3 fatty acids, copper, iron, iodine, manganese, selenium, zinc, B-vitamins) in the human food chain (De Smet and Vossen, 2016). However, despite the benefits of meat consumption, the increase in the number of livestock directly challenges the sustainability of animal production because it profoundly impacts our planet. The General Assembly of the United Nations has defined the goals of sustainable agriculture to ensure economic viability, protect natural resources, provide ecosystem services, manage rural areas, improve the quality of life in agricultural areas, ensure animal welfare and produce safe and healthy food (UN, 2015). The EU goals for animal production are in particular to increase the competitiveness and economic viability of animal production systems, to improve livestock's adaptation to diseases and increasingly extreme weather patterns related to climate change, to address issues related to diet and health, ammonia and air quality, and issues related to greenhouse gas emissions and climate change, nitrate emissions and degradation of natural resources such as water, soil and biodiversity, global food security, global trade and animal welfare (ERANET, 2020). The negative impact of livestock production on our earth can be reduced by two alternative scenario's for improving the sustainability of future pig production systems (Rauw *et al.*, 2020). The first scenario is a high input-high output system based on sustainable intensification, maximising animal protein production efficiency on a limited land surface at the same time as minimising environmental impacts. The second scenario is a reduced input-reduced output system based on selecting animals that are more robust to climate change and are better adapted to transform low quality feed (local feeds, feedstuff co-products, food waste) into meat. Sustainability can be increased with a shift from dependence on optimally formulated feed based on imported feed ingredients and use of feed grains to use of feeds based on locally produced ingredients and co-products not fit for use as human food (Mottet *et al.*, 2017). Soybean meal has a relatively high protein content (45-50%) with an adequate amino acid profile, low variation in nutrient composition, and contains anti-nutritional factors that are easily reduced by heat processing and is therefore a suitable ingredient in pig diets. It is an important source of the amino acid lysine, which is the first limiting amino acid in diets for pigs (De Visser *et al.*, 2014), and other essential amino acids. Therefore, more than 50% of the total dry matter (DM) intake of pigs is based on cereals, while 9-25% is covered by oil meals, including soybean meal. In the European Union, soybean meal is the major oil seed meal consumed in animal nutrition and a large percentage of the used soybean is imported, because European production of soybean is low, compared to other oil seeds (Florou-Paneri *et al.*, 2014). The inclusion of other oilseed meals to reduce dependence on imported soybean meal, such as sunflower meal or rapeseed meal in pig diets can provide opportunities to diversify the feed matrix by using home-grown feed ingredients. These alternative feed ingredients can partially or completely replace soybean meal in pig feed, especially during growing and finishing periods. There are other protein sources that can be used for pig nutrition, such as cottonseed meal, flaxseed meal, peas and faba beans. A potential alternative protein source for animal and pig feed are also insects and insects derived products which have a lower environmental footprint related to lower land use, water use and less emissions (Van Huis and Oonincx, 2017).

4. Pig production systems and pig nutrition

Specialised pig farms generally have a large number of animals. In specialised pig farming, three types of business can be created, such as breeding farms, finishing farms, farrowing to finisher farms, and there are also farms that keep pigs as an auxiliary activity (Anonymous, 2017). Breeding farms are involved in piglet production. Sow milk is the most important source of nutrients for piglets. Milk also contains protective substances (e.g. immunoglobulins) against multiple pathogens. At weaning at about four weeks of age, piglets have to change from fluid to solid feed. This requires adjustments of the digestive system and further development of the immune system. Generally highly digestible ingredients and protein sources are used in piglets in the post-weaning phase (whey, soybean derived protein sources, cooked cereals and fish meal). Weaning also include transfer of piglets to a new environment. This transition to a change in feed is often accompanied by a decrease in feed intake (FI) and a risk for infection by pathogenic *Escherichia coli* and streptococci inducing health disorders. Piglets are transferred to a finishing pig farm when they weigh around 25 kg (age about 10 weeks). The finishing pig farm is dedicated to raise piglets to finishing pigs. The pigs stay here until they weigh about 120 kg (age about 6 months). The pigs are then slaughtered and processed into pig meat for consumption by consumers. The dietary protein and essential amino acid requirements decrease as pigs grow older. To maximise piglet growth, it is recommended that levels of crude protein (CP) be at 20-23% in pre-starter and 18-20% in starter diets. Recommended levels of crude protein in finisher diets decrease from about 19% at 10 weeks of age to 13% in the pre-slaughter phase. Most common feed ingredients used in finisher diets are cereals such as corn and wheat and the remainder mainly consists of soybean meal, sunflower seed meal, wheat middlings and palm kernel meal. Use of soybean meal, the major protein source included in pig diets, has a large environmental impact due to land and water use to grow soybeans and the large-scale and -distance transportation of this ingredient (Wiedemann *et al.*, 2016). Replacement of soybean meal with locally derived vegetal protein sources will reduce requirements for transport but land use will not reduce. By use of insects as feed ingredient associated transport and land use will reduce (Van Zanten *et al.*, 2018).

5. Chemical composition of insect species

In a feasibility study, Veldkamp *et al.* (2012) concluded that the use of insects as a sustainable protein-rich feed ingredient in pig and poultry diets is possible based on their nutritional value but their maximum inclusion levels to replace traditional protein sources should be studied further. The amino acid profile of yellow mealworm (*Tenebrio molitor*; TM), common housefly (HF), and black soldier fly (BSF) is close to the profile of soybean meal (Veldkamp and Bosch, 2015). The chemical composition of the insect species included in the present review – BSF prepupae products, HF larval meal and mealworm larvae – and the traditional protein sources soybean meal and fishmeal is presented in Table 1. The protein content of the insect species is comparable to soybean meal but lower than fishmeal and the fat content of the insect species is higher than in soybean meal and fishmeal. The amino acid profile of the insect species is close to the profile in soybean meal and fishmeal.

To compete with conventional protein sources for animal feeds and to become an interesting link in the animal feed chain to meet the growing global demand for protein, the cost price of insect production must be further reduced. However, insect production and related research are just in their infant stage. Literature on possible beneficial effects of insect products as feed ingredient on health of livestock animals is still scarce. Beneficial health effects of including insect products in pig diets may give applications in pig production an added value. Presence of chitin, lauric acid and antimicrobial peptides in insects as potential functional constituents may have positive health effects in monogastric animals (Dörper *et al.*, 2021; Gasco *et al.*, 2018; Jozefiak and Engberg, 2017).

6. Digestibility of insect products and insect-based diets

In total, five experiments were found with weaned piglets and two experiments with growing pigs. In five experiments different mealworm products were tested and in two experiments BSF products were tested. Most of the digestibility experiments are based on exchange of a traditional protein source by insect protein and so nutrient digestibility in these experiments has been evaluated at the level of the diet. Only in two papers the digestibility of the insect protein as such was evaluated. With respect to digestibility of diets as presented in Table 2 it should be noted that the nutrient digestibility of diets is affected by the nature of exchange of protein sources in the diet. Therefore, these values should be judged in this context.

Weaned piglets

Nutrient digestibility in weaned piglets was determined for 0, 1 and 2% inclusion of dried *Ptecticus tenebrifer* (PT) larvae at the expense of fishmeal (Ao and Kim, 2019). The apparent total tract digestibility (ATTD) of DM (78.8 vs 81.9%, respectively) and N (78.6 vs 81.6%, respectively) was at 1% PT inclusion lower than at the control diet at 56 d of age. Also Meyer *et al.* (2020) observed that ileal digestibility of all amino acids in weaned piglets at 63 d of age, except aspartic acid, were 6.7 to 15.6% lower at 10% TM inclusion than at 0% TM inclusion. Contrary to Ao and Kim (2019) and Meyer *et al.* (2020), nitrogen retention and apparent total tract digestibility of DM and CP linearly increased when weaned piglets were fed diets with increasing inclusion levels of ground dried TM larvae (Jin *et al.*, 2016). Digestibility of DM and CP increased from 90 to 94% and from 86 to 93%, respectively at 0% and 6% TM larvae inclusion (Jin *et al.*, 2016). Nitrogen retention increased linearly from 2.2 to 2.4 g/d at 0 and 6% TM larvae inclusion, respectively. It should be noted that

Table 1. Chemical composition of black soldier fly prepupae products, housefly larval meal, mealworm larvae, soybean meal and fishmeal.[1]

	BSF prepupae grown on vegetable waste	Full fat BSF larval meal	Partially defatted BSF larval meal	HF larval meal	TM larvae	Soybean meal	Fishmeal
g/kg							
Dry matter	410	884	939	920	381	877	913
Crude ash	96	74	68	65	24	64	168
Crude protein	399	425	408	533	491	467	629
Crude fat	371	325	128	203	352	15	98
Ca	28.7	20.8	5.8	–	0.4	2.9	40.3
P	4.0	4.7	7.6	–	7.5	6.4	26.0
g/16 g N							
Lys	5.7	6.2	6.2	7.1	5.5	6.2	7.6
Met	1.9	2.5	2.9	2.5	1.3	1.4	2.8
Cys	0.5	0.7	1.5	2.8	0.9	1.5	0.9
Thr	3.9	4.2	4.0	5.3	5.1	3.9	4.2
Trp	1.5	–	–	6.5	4.1	1.3	1.1
Ile	4.3	5.6	4.9	3.6	5.0	4.6	4.2
Arg	5.0	5.7	5.2	4.8	5.2	7.5	5.9
Phe	4.1	5.5	4.4	6.0	3.5	5.2	3.9
His	3.1	3.7	3.0	2.9	3.2	2.7	2.6
Leu	7.0	8.6	7.6	6.1	10.6	7.7	7.3
Tyr	–	–	–	6.5	0.8	3.7	3.1
Val	6.2	7.2	6.7	4.3	7.3	4.8	4.9
Ala	6.1	7.3	8.2	5.5	8.2	4.4	6.3
Asp	9.0	11.0	10.3	9.9	8.1	11.6	9.3
Glu	10.4	11.6	15.3	13.4	11.3	17.8	13.0
Gly	5.6	7.2	6.2	4.5	5.6	4.3	6.5
Pro	5.4	7.2	7.8	3.8	7.0	5.1	4.4
Ser	3.8	4.8	5.0	2.5	5.1	5.1	4.0
Sum_AA	83.3	99.0	99.4	97.9	97.8	98.8	92.0
Reference	adapted from Spranghers *et al.* (2017)	adapted from Crosbie *et al.* (2020)	adapted from Crosbie *et al.* (2020)	adapted from Hall *et al.* (2018)	adapted from Finke (2002)	CVB (2019)	CVB (2019)

[1] AA = amino acid; Ala = alanine; Arg = arginine; Asp = aspartate; BSF = black soldier fly (*Hermetia illucens*); Ca = calcium; Cys = cysteine; Glu = glutamate; Gly = glycine; HF = housefly (*Musca domestica*); His = histidine; Ile = isoleucine; Leu = leucine; Lys = lysine; Met = methionine; N = nitrogen; P = phosphorus; Phe = phenylalanine; Pro = proline; Ser = serine; Thr = threonine; TM = mealworm (*Tenebrio molitor*); Trp = tryptophan; Tyr = tyrosine; Val = valine.

this is only partly due to improved digestibility and more to the complete nutrient balance of the diets.

Biasato *et al.* (2019) concluded that ATTD was not affected in weaned piglets fed diets with 0, 5 and 10% inclusion of partially defatted BSF larval meal at the expense of soybean meal at 23 d of age as well as at 61 d of age. Spranghers *et al.* (2018) evaluated ATTD and apparent ileal digestibility (AID) of full-fat BSF and defatted BSF in weaned piglets from 21 to 36 d of age. Full-fat BSF was included in the diet at 4 and 8% and defatted BSF was included in the diet at a level supplying a similar level of protein to the diet as the diet with defatted BSF at 8% and those treatments were compared with a control diet without BSF. Full-fat BSF or defatted BSF were included in the diet at the expense of toasted soybeans. ATTD of crude protein of the control diet did not differ significantly to that of the insect-containing feed (crude protein digestibility between 77 and 78% for all treatments). Whereas the AID of crude protein in the 8% full-fat BSF diet (67.4%) was lower than that in the control diet (69.7%), the crude protein digestibility for the 4% full-fat and the defatted BSF diets was higher (73.3%) (Spranghers *et al.*, 2018).

Table 2. Nutrient digestibility of insect products and insect-based pig diets.[1]

Pig species/type	Age (d)	Insect product	Target replacement	Insect inclusion %	Results	Reference
Weaned piglets	21-36	Full-fat BSF and defatted BSF	Toasted soybeans	0, 4, 8	AID of CP in the 8% full-fat BSF diet was lower than that of the control diet and AID of CP in the 4% full-fat and the defatted BSF diets was higher.	Spranghers *et al.* (2018)
Weaned piglets ([Duroc× Yorkshire]×Landrace)	21-56	Dried mealworm (PT) powder	Fishmeal	0, 1, 2	ATTD of DM and N at 1% inclusion was lower than in the control diet.	Ao and Kim (2019)
Weaned piglets (Topigs)	21-61	Partially defatted BSF larval meal	Soybean meal	0, 5, 10	ATTD was not affected by dietary treatment.	Biasato *et al.* (2019)
Weaned piglets ([Yorkshire× Landrace]×Duroc)	28-63	Ground air-dried TM larvae	Soybean meal and soy oil	0, 1.5, 3.0, 4.5, 6.0	Nitrogen retention and ATTD of DM and CP linearly increased with increasing TM levels.	Jin *et al.* (2016)
Weaned piglets (Piétrain× [German Landrace×German Edelschwein])	35-63	TM larvae	Soybean meal	0, 5, 10	AID of all AAs, except aspartic acid, was lower at 10% inclusion than at the control diet.	Meyer *et al.* (2020)
Growing pigs ([Landrace× Yorkshire]×Duroc)	24 kg	Dried TM larvae powder	Fishmeal, meat meal, poultry meal	9.95	SID of DM, CP, total AAs, essential AAs and non-essential AAs tended to be higher than fishmeal, meat meal and poultry meal.	Yoo *et al.* (2019)
Growing pigs ([Landrace× Yorkshire]×Duroc)	29 kg	100% defatted TM larval meal and TM larvae hydrolysate	Soybean meal	0, 10	AID of DM, CP, Lys, Met and Thr in TM larvae hydrolysate was higher compared to fermented poultry by-product and hydrolysed fish soluble.	Cho *et al.* (2020)

[1] AAs = amino acids; AID = apparent ileal digestibility; ATTD = apparent total tract digestibility; BSF = black soldier fly (*Hermetia illucens*); CP = crude protein; DM = dry matter; Lys = lysine; Met = methionine; N = nitrogen; PT = mealworm (*Ptecticus tenebrifer*); SID = standardised ileal digestibility; Thr = threonine; TM = mealworm (*Tenebrio molitor*).

Growing pigs

Yoo *et al.* (2019) determined standardised ileal digestibility (SID) of TM larvae powder, fishmeal, meat meal and poultry meal at an inclusion level of 9.95% in growing cannulated pigs of 24 kg. The SID of Arg was higher ($P<0.05$) in pigs fed TM diet compared to that in pigs fed fish meal or meat meal diets (90.0 vs 87.6 and 88.0%, respectively). Furthermore, pigs fed poultry meal, meat meal, or TM diet showed increased ($P<0.05$) SID of Cys compared to pigs fed fish meal diet (88.4, 86.6, 90.2 vs 83.6%, respectively). Pigs fed the TM diet tended to show increased SID of DM, total energy, CP, total amino acids (AAs), the other essential AAs (Lys, Met, Thr, Val, Ile, Leu, Phe and His), and the other non-essential AAs (Asp, Ser, Glu, Gly, Ala, Tyr and Pro) than pigs fed meat meal, poultry meal, or fish meal diet. In another study with growing pigs the AID of 100% defatted TM and TM larvae hydrolysate was determined in cannulated pigs of 29 kg (Cho *et al.*, 2020). Pigs fed the hydrolysate of TM diet had higher SIDs of DM and CP (93.3% and 93.2%; $P<0.05$, respectively) compared to pigs fed the other fermented poultry by-product and hydrolysed fish soluble diets. In the case of SIDs of total AAs although there was no difference between treatments ($P=0.06$), pigs fed diets with hydrolysate of TM (83.4%) showed higher digestibility, followed by those fed with fermented poultry by-product (82.0%), defatted TM (81.9%) and hydrolysed fish soluble diets (79.2%). For SID of Lys, Met and Thr, pigs fed hydrolysate of TM and defatted TM larval meal diets showed higher SIDs (P=0.05, P<0.05 and P<0.05, respectively) than pigs fed fermented poultry by-product and hydrolysed fish soluble diets. SIDs of non-essential amino acids (Asp, Gly, Ala) were higher (P<0.05, P<0.05 and P<0.05, respectively) in pigs fed hydrolysate of TM, fermented poultry by-product, and defatted TM larval meal diets than those in pigs fed the hydrolysed fish soluble diet. AID and SID of Glu were higher in pigs fed hydrolysate of TM and fermented poultry by-product diets.

The two papers evaluating the SID of crude protein and amino acids in insect products are presented in Table 3 (Crosbie *et al.*, 2020; Tan *et al.*, 2020).

Crosbie *et al.* (2020) evaluated SID of amino acids and net energy contents in full fat and defatted BSF larval meals in growing pigs (Table 3). SID of CP (80.6%) and Lys (88%) were not different between full-fat BSF larval meal and partially defatted BSF larval meal. SID of the essential amino acids Arg (respectively 92.7 vs 95.9%) and Val (respectively 83.2 vs 88.4%) was lower and SID of Met (respectively 90.2 vs 79.3%) was higher for full-fat BSF larval meal versus partially defatted BSF larval meal. In addition, the authors conclude that full-fat BSF larval meal was a better source of net energy for growing pigs than partially defatted BSF larval meal (3,479 vs 2,287 kcal/kg DM, respectively). Tan *et al.* (2020) determined the AID and the SID of amino acids in HF and BSF prepupae meal in growing pigs (25 kg). AID and SID of all essential amino acids in HF were higher than in BSF in growing pigs. Nutrient digestibility coefficients of defatted BSF larval meal and HF larval meal were in general comparable with digestibility coefficients of soybean meal and fishmeal except for Met which was in partially in BSF larval meal (79.3%) lower than in soybean meal (90.0%) and fishmeal (89.0%). Nutrient digestibility of HF larval meal was higher than BSF larval meal.

In summary, digestibility of dietary nutrients showed variation in weaned piglets when soybean meal and fishmeal were replaced by TM and when soybean meal and toasted soybeans were replaced by BSF larval meal. In growing pigs, TM inclusion in the diet resulted in a higher nutrient digestibility compared to fishmeal, hydrolysed fish soluble, meat meal, poultry meal and fermented poultry by-product based diets. The variability in nutrient digestibility of insect products in different studies is mainly due to changes in diet composition when insect products are included. The heterogeneity of the results in studies may also be attributed to the insect species, the insect life stage (adult, larva or pupa), the insect rearing substrate, and processing techniques and conditions (temperature at drying, extraction techniques, chitin removal) which all may influence the nutritive value of the insect products used (Barragan-Fonseca *et al.*, 2017; Cho *et al.*, 2020; Crosbie *et al.*, 2020; Gasco *et al.*, 2019; Sánchez-Muros *et al.*, 2014). Two digestion experiments were conducted in which the only protein source was the insect protein source of consideration. From these two experiments with full-fat BSF larval meal, partially defatted BSF larval meal,

Table 3. Standardised ileal digestibility of crude protein and essential amino acids in black soldier fly prepupae products and housefly prepupae meal, soybean meal and fishmeal.[1]

	Full fat BSF larval meal	Partially defatted BSF larval meal	BSF prepupae meal	HF prepupae meal	Soybean meal	Fishmeal, treated
%						
Crude protein	80.2	81.0	-	-	87.0	85.0
Lys	86.8	89.1	77.6	91.8	89.0	89.0
Met	90.2	79.3	91.8	98.8	90.0	89.0
Thr	87.2	86.6	79.8	91.9	85.0	88.0
Ile	87.2	89.6	77.5	87.8	88.0	90.0
Arg	92.7	95.9	86.2	97.3	93.0	92.0
Phe	95.4	97.6	76.7	90.6	89.0	87.0
His	80.7	84.3	77.8	89.6	90.0	87.0
Leu	87.2	90.7	81.0	91.8	87.0	90.0
Val	83.2	88.4	80.9	91.0	87.0	89.0
Reference	Crosbie *et al.* (2020)	Crosbie *et al.* (2020)	Tan *et al.* (2020)	Tan *et al.* (2020)	CVB (2019)	CVB (2019)

[1] Arg = arginine; BSF = black soldier fly (*Hermetia illucens*); HF = housefly (*Musca domestica*); His = histidine; Ile = isoleucine; Leu = leucine; Lys = lysine; Met = methionine; Phe = phenylalanine; Thr = threonine; Val = valine.

and HF larval meal it can be concluded that amino acid digestibility of the evaluated insect products is comparable to the amino acid digestibility of soybean meal and fishmeal. HF larval meal amino acid digestibility was higher than in BSF larval meal.

7. Growth performance

In literature, one experiment was conducted with nursing piglets, six with weaned piglets, two with growing pigs and one with finishing pigs (Table 4). In three experiments different mealworm products were tested, six experiments with BSF products and one experiment with HF.

Nursing piglets

Driemeyer (2016) studied the effect of 3.5% BSF larvae inclusion at the expense of fishmeal in pig creep diets on growth performance from 10 to 28 days of age. FI and body weight gain (BWG) were not affected by dietary treatment.

Weaned piglets

In an experiment of (Ao and Kim, 2019) body weight (BW) at 1% PT inclusion was lower than at control diet at 56 d of age (21.0 vs 21.8 kg, respectively). Feed conversion ratio (FCR) at 1 and 2% PT inclusion was higher from 21 to 28 d of age (1.24 and 1.23, respectively) than for the control diet (1.17). Inclusion of 5 or 10% TM in diets for weaned

Table 4. Growth performance in pigs fed insect products.[1]

Pig species/type	Age (d)	Insect product	Target replacement	Insect inclusion %	Results	Reference
Nursing piglets (Large White and Landrace)	10-28	Milled and sieved (3 mm) BSF larvae	Fishmeal	0, 3.5	Growth performance was not affected.	Driemeyer (2016)
Weaned piglets	21-36	Full-fat BSF and defatted BSF	Toasted soybeans	0, 4, 8	Growth performance was not affected.	Spranghers *et al.* (2018)
Weaned piglets ([Duroc× Yorkshire]×Landrace)	21-56	Dried mealworm (PT) powder	Fishmeal	0, 1, 2	Final BW at 1% inclusion was lower than at control diet. FCR at 1 and 2% inclusion was higher than at control diet. BWG at 1% inclusion was lower than at control diet during 29-42 and 21-56 d of age.	Ao and Kim (2019)
Weaned piglets (Topigs)	21-61	Partially defatted BSF larva meal	Soybean meal	0, 5, 10	FI in phase II increased linearly with increasing inclusion levels.	Biasato *et al.* (2019)
Weaned piglets	21-61	BSF larvae oil	Corn oil	0, 2, 4, 6	BW and BWG increased linearly and FCR decreased linearly at increasing inclusion levels.	Van Heugten *et al.* (2019)
Weaned piglets ([Yorkshire× Landrace]×Duroc)	28-63	Ground air-dried TM larvae	Soybean meal and soy oil	0, 1.5, 3.0, 4.5, 6.0	FI, BW and BWG increased linearly at increasing inclusion levels during phase I (28-42 d).	Jin *et al.* (2016)
Weaned piglets (Piétrain× [German Landrace×German Edelschwein])	35-63	TM larvae	Soybean meal	0, 5, 10	BWG at 10% inclusion was lower than at 0% and 5% inclusion.	Meyer *et al.* (2020)
Growing pigs (Large White)	11-29 kg	Ground sun-dried HF larvae	Fishmeal	0, 10	BWG was higher and FCR was lower for HF larvae-fed pigs compared to fishmeal-fed pigs.	Dankwa *et al.* (2000)
Growing pigs (Large White× Landrace)	18-53 kg	Dried BSF larval meal	Fishmeal	0, 9, 12, 14.5, 18.5	Growth performance was not affected.	Chia *et al.* (2019)
Finishing pigs ([Duroc× Landrace]×Large White)	76-115 kg	Dried BSF larvae powder	Soybean meal	0, 4, 8	BW and BWG at 4% inclusion was higher and FCR was lower than at 0 and 8% inclusion.	Yu *et al.* (2019)

[1] BSF = black soldier fly (*Hermetia illucens*); BW = body weight; BWG = body weight gain; FCR = feed conversion ratio; FI = feed intake; HF = housefly (*Musca domestica*); PT = mealworm (*Ptecticus tenebrifer*); TM = mealworm (*Tenebrio molitor*).

piglets from 35 to 63 d of age did not affect performance parameters (FI, BW, FCR) (Meyer *et al.*, 2020). Only daily BWG was lower in pigs fed diets with 10% TM compared to pigs fed control diets and 5% inclusion level (573 vs 636 and 614 g/d, respectively). The authors stated, however, that the number of pigs in the study is rather limited and the number of observations is rather low for a classical performance trial. Jin *et al.* (2016) included dried TM (0, 1.5, 3.0, 4.5 and 6.0%) at the expense of soybean meal and studied the effects on growth performance of weaned piglets. FI, BW and BWG improved linearly when the piglets were fed increasing levels of TM larvae in feeding phase I (28-42 d of age). BWG tended (P=0.08) to increase linearly at increasing TM levels during phase II (42-63 d of age) and overall FCR tended (P=0.07) to improve linearly at increasing TM levels up to the highest inclusion level of 6%.

Biasato *et al.* (2019) reported that growth performance was not affected in weaned piglets fed a two-phase diet except for FI in phase II. A linear response of FI to increasing BSF meal levels (0, 5 and 10% BSF larval meal) was observed (940, 950 and 970 g/d, respectively). Spranghers *et al.* (2018) studied also the effect on growth performance of weaned piglets fed diets with 4 and 8% full-fat BSF and 5.4% defatted BSF from 21 to 36 d of age. Defatted BSF was included in the diet at a level supplying a similar level of protein to the diet as the diet with defatted BSF at 8% and those treatments were compared with a control diet without BSF. BSF was included in the diet at the expense of toasted soybeans. Growth performance (FI, BWG and FCR) was not affected by dietary treatment.

Growing pigs

In growing pigs partial or full replacement of fishmeal in diets by BSF larval meal up to 18.5% BSF larvae inclusion at full replacement of fishmeal did not affect FI, BWG and FCR (Chia *et al.*, 2019).

When 10% ground sun-dried HF larvae was included to replace 10% fishmeal in growing pig diets, CP content of the diets was almost similar and crude fat content in the diets with HF larvae was higher than in fishmeal diets (Dankwa *et al.*, 2000). In the growth period from 11 to 29 kg daily BWG of pigs fed diets with 10% HF larvae was higher (290 vs 250 g/d, respectively) and FCR was lower (3.29 vs 3.64, respectively) compared to pigs fed diets containing 10% fishmeal (Dankwa *et al.*, 2000).

Finishing pigs

In finishing pigs (76-115 kg) inclusion of 4% dried BSF larvae powder at the expense of soybean meal resulted in a higher final BW (120 vs 116 and 115 kg, respectively) and BWG (980 vs 890 and 860 g/d) and a lower FCR (2.85 vs 3.21 and 3.24, respectively) compared to 0 and 8% inclusion (Yu *et al.*, 2019). FI was not affected by dietary inclusion of BSF larvae powder. The authors suggested that the underlying mechanism may be associated with the up-regulated expression of genes related to the lipogenic potential and muscle fibre composition. The lack of positive effects in the finishing pigs fed diets with 8% BSF larvae may be due to the higher level of chitin in the BSF larvae diet.

Next to insects as dietary protein source one study evaluated the inclusion of insect oil in diets for weaned piglets. The impact of increasing levels of supplemental BSF larvae oil on growth performance was studied in weaned piglets from 21 to 61 d of age (Van Heugten *et al.*, 2019). Treatments consisted of 0, 2, 4 and 6% supplemental BSF larvae oil, replacing equal amounts of corn oil. Supplementation of BSF larvae oil linearly increased BW and BWG until 46 d of age and overall. FCR was improved linearly until 46 d of age, and FI was not affected.

In summary growth performance was not affected by BSF larvae inclusion in an experiment with nursing piglets. Effects of mealworm and BSF larvae inclusion in weaned piglets diets on growth performance results were not consistent. In an experiment with growing pigs dietary inclusion of BSF larvae replacing fishmeal did not affect growth performance and in an experiment with growing pigs dietary inclusion of HF larvae replacing fishmeal improved growth performance. In finishing pigs an inclusion of 4% BSF larvae replacing soybean meal resulted in an improved growth performance compared to 0 and 8% inclusion. Including BSF larvae oil replacing corn oil up to 6% improved growth performance linearly in weaned piglets. The effect of insect products on growth performance results is highly dependent on study design, formulation of the diets and the nutritional value of insects included in the feed formulation matrix. Some of the effects observed related to the dietary inclusion of insects products are likely also related to the previous points.

8. Carcass and meat quality

Two studies are included reporting the effects of dietary insect inclusion on carcass and meat quality. In one experiment product quality was observed in growing pigs and in one experiment in finishing pigs. One study was based on HF larvae and one study on BSF larvae.

Growing pigs

Dankwa *et al.* (2000) replaced 10% fishmeal by ground sun-dried HF larvae in diets for growing pigs. Replacement did not affect dressing percentage and eye muscle area. Shoulder fat content in pigs fed sun-dried HF larvae was higher (3.02 vs 2.65 cm, respectively) than fat content in growing pigs fed fishmeal. This can be the result of excess energy in the diet containing HF larvae.

Finishing pigs

In finishing pigs (76-115 kg) dietary inclusion of dried BSF larvae powder at the expense of soybean meal affected carcass and meat quality (Yu *et al.*, 2019). Inclusion of 4% BSF larvae powder in the diet improved carcass traits and muscle chemical composition of finishing pigs and affected the meat quality via upregulating the expression of genes related to the lipogenic potential and muscle fibre composition in the longissimus thoracis of pigs. Loin-eye area (54.7 and 49.3 cm vs 45.4 cm, respectively) was increased at 4 and 8% compared with the control treatment.

9. Health

Different health related parameters were measured in eight studies reported in literature with insect inclusion in the diet (Table 5). One experiment was conducted with nursing piglets, six with weaned piglets and one experiment with growing pigs. Two studies were conducted in which TM products were included and in six studies BSF products were included.

Nursing piglets

Driemeyer (2016) investigated the effect of BSF larval meal supplementation on nursing piglet blood parameters of 28 litters in two treatments (a control diet with 0% larval meal inclusion and a diet with 3.5% inclusion of larval meal). Inclusion of 3.5% BSF larval meal in pig creep diets did not affect haematological and biochemical concentrations at 28 days of age. However, the author reported that the BSF larval meal diet showed an increased haemoglobin concentration and a higher haematocrit value. According to the author, these results may be considered as an indication of immunological stress, however, the animals did not show physical signs of distress when compared to the control group.

Weaned piglets

Meyer *et al.* (2020) concluded that TM meal can be used as a dietary source of protein in weaned pigs without causing adverse effects on intermediary metabolism. The highest TM meal inclusion level in this study was 10%. Plasma metabolomics revealed higher concentrations of Ala, Asp, Glu, Pro, Ser, Tyr and Val and a lower concentration of Asn at 10% inclusion than at control diet. Only one out of fourteen quantifiable amino acid metabolites, namely methionine sulfoxide (MetS), in plasma was elevated by 45% and 71% at 5 and 10% inclusion, respectively, compared to control diet (P<0.05). Plasma concentrations of both, major carnitine/ acylcarnitine species and bile acids were not different across groups. Lipidomics of liver and plasma demonstrated no differences in the concentrations of triacylglycerols, cholesterol and the main phospholipids, lysophospholipids and sphingolipids between groups. It was concluded that TM can be used as a dietary source of protein in pigs without causing adverse effects on metabolism of growing pigs. Jin *et al.* (2016) determined blood profiles in weaned piglets fed different TM inclusion levels. Blood urea nitrogen decreased linearly and insulin-like growth factor (IGF-1) increased linearly at increasing TM levels in phase II (42-63 d). High levels of blood urea nitrogen indicate that excessive amino acids are metabolised and circulate in the blood. IGF-1 as growth hormone plays an important role in controlling the structure, function of cardiovascular system and skeletal maturation (Bayes-Genis *et al.*, 2000). Blood immunoglobulin A (IgA) and G concentrations were measured as indicators of the immune response but were not affected by inclusion of TM in diets for weaned piglets.

Biasato *et al.* (2019) studied haematological, biochemical, morphometric and histopathological parameters in weaned piglets fed 0, 5 or 10% partially defatted BSF larvae at the expense of soybean meal. The parameters were not affected, except for the counts of monocytes and neutrophils, a linear and quadratic response was observed, respectively, to increasing BSF meal levels (with the maximum values corresponding to 10 and 5% BSF inclusion, respectively). This finding is difficult to explain, since none of the BSF-fed piglets showed any signs of physical distress or inflammatory diseases. Spranghers *et al.* (2018) studied intestinal health parameters in weaned piglets at 36 d of age fed diets with full-fat BSF and defatted BSF. Full-fat BSF was included at 4 and 8% and defatted BSF at a level supplying a similar level of protein to the diet as the diet with defatted BSF at 8%. pH, Lactobacilli and Streptococci in stomach, proximal small intestine and distal small intestine were not affected by dietary treatment despite higher measured lauric acid concentrations in the different segments at both inclusion levels of full-fat BSF. Alteration of intestinal specific bacterial populations and immune homeostasis in weaned piglets fed BSF larval meal as a fishmeal replacement was studied from 28 to 56 d of age (Yu *et al.*, 2020). BSF larval meal was included at 1, 2 and 4% at the expense of fishmeal. Inclusion of 2% BSF larval meal (replacement for 50% of dietary fishmeal) affected specific ileal and caecal bacterial populations and metabolic profiles, as well as the expression of mucosal immune genes. Dietary inclusion of 2% BSF larval meal selectively increased the number of certain probiotic bacteria, and the concentration of lactate and short chain fatty acids in the ileal and caecal digesta. Additionally, it selectively decreased the number of *E. coli* and the concentration of metabolites involved in nitrogen metabolism (branched chain fatty acids, biogenic amines, and phenolic and indolic compounds). The ileum mucosal mRNA expression of TLR4-MyD88-NF-κB signalling pathway and proinflammatory cytokine genes, and TNF-α protein concentration were decreased, but the mRNA expression of barrier function-, development-

Table 5. Health of pigs fed insect products.[1]

Pig species/type	Age (d)	Insect product	Target replacement	Insect inclusion %	Results	Reference
Nursing piglets (Large White and Landrace)	10-28	Milled and sieved (3 mm) BSF larvae	Fishmeal	0, 3.5	Evaluated haematological and biochemical parameters were not affected.	Driemeyer (2016)
Weaned piglets	21-36	Full-fat BSF and defatted BSF	Toasted soybeans	0, 4, 8	pH, Lactobacilli and D-Streptococci in stomach, proximal small intestine and distal small intestine were not affected.	Spranghers *et al.* (2018)
Weaned piglets (Topigs)	21-61	Partially defatted BSF larva meal	Soybean meal	0, 5, 10	Evaluated haematological and biochemical parameters were not affected, except for the monocytes and neutrophils, linear and quadratic responses were observed. Gut morphology and histological features were not affected.	Biasato *et al.* (2019)
Weaned piglets	21-61	BSF larvae oil	Corn oil	0, 2, 4, 6	Evaluated biochemical parameters were not affected, except cholesterol that increased linearly at higher inclusion levels. Haematological parameters were not affected, but platelet count tended to linearly increase at higher inclusion levels.	Van Heugten *et al.* (2019)
Weaned piglets ([Duroc × Landrace] × Large White)	28-56	Full-fat BSF larval meal	Fishmeal	0, 1, 2, 4	Supplementation with 2% BSF larval meal affected specific ileal and caecal bacterial populations and metabolic profiles, as well as the mucosal immune genes expression.	Yu *et al.* (2020)
Weaned piglets ([Yorkshire×Landrace]×Duroc)	28-63	Ground air-dried TM larvae	Soybean meal and soy oil	0, 1.5, 3.0, 4.5, 6.0	Blood urea nitrogen decreased linearly and insulin-like growth factor increased linearly at increasing inclusion levels in phase II (42-63 d). Immunoglobulin A and G concentrations were not affected.	Jin *et al.* (2016)
Weaned piglets (Piétrain × [German Landrace × German Edelschwein])	35-63	TM larvae	Soybean meal	0, 5, 10	Higher blood plasma concentrations of Ala, Asp, Glu, Pro, Ser, Tyr and Val and a lower concentration of Asn at 10% inclusion than at control diet. Plasma methionine sulfoxide was higher at 5% and 10% inclusion, compared to control diet.	Meyer *et al.* (2020)
Growing pigs (Large White × Landrace)	18-53 kg	Dried BSF larval meal	Fishmeal	0, 9, 12, 14.5, 18.5	Red or white blood cell parameters were not affected, except for neutrophil counts, which were higher at 14.5 and 18.5% inclusion compared to control diet. Platelet counts at 9, 14.5 and 18.5% inclusion were lower compared to control diet and 12% inclusion. Blood cholesterol levels were not affected.	Chia *et al.* (2019)

[1] Ala = alanine; Asn = asparagine; Asp = aspartate; Glu = glutamate; Pro = proline; Ser = serine; Tyr = tyrosine; Val = valine; BSF = black soldier fly (*Hermetia illucens*); Ig = immunoglobulin; TM = mealworm (*Tenebrio molitor*).

relative, and anti-inflammatory cytokines and sIgA protein concentrations were increased.

Growing pigs

Chia *et al.* (2019) studied blood parameters in growing pigs fed different inclusion levels of BSF larvae as blood profiles can provide an indication of the clinical health status as well as the extent to which dietary deficiencies impact the physiological status of the animal. Red or white blood cell concentrations were not affected at any inclusion level of BSF larval meal in diets for growing pigs (Chia *et al.*, 2019) up to inclusion level of 18.5% at full replacement of fishmeal in the diet. Neutrophil counts were higher at 14.5 and 18.5% inclusion compared to control. Neutrophils are one of the first responders of inflammatory cells to migrate toward the site of inflammation. Platelet counts at 9, 14.5 and 18.5% inclusion were lower compared to 0 and 12% inclusion. Low platelet concentration implies that blood clotting might be impaired, resulting in blood loss in case of injury (Etim *et al.*, 2014).

Van Heugten *et al.* (2019) studied the impact of increasing levels of supplemental BSF larval oil on serological and haematological indices in weaned piglets from 21 to 61 d of age. Treatments consisted of 0, 2, 4 and 6% supplemental BSF larval oil, replacing equal amounts of corn oil. Supplemental BSF larval oil did not affect serological parameters, but linearly increased serum cholesterol. Haematological parameters were also not affected by BSF larval oil, but platelet count tended (P=0.082) to linearly increase at increased BSF larval oil inclusion levels.

Overall it can be summarised that health related haematological, biochemical and intestinal health parameters were not affected by dietary inclusion of insect products. Only in one study inclusion of 2% BSF larval meal (replacement 50% of dietary fishmeal) affected specific ileal and caecal bacterial populations and metabolic profiles, as well as the ileal immune status in weaned piglets.

10. Conclusions

Amino acid digestibility of full-fat BSF larval meal, partially defatted BSF larval meal and HF larval meal were comparable to the amino acid digestibility of soybean meal and fishmeal and HF larval meal amino acid digestibility was higher than in BSF larval meal. Nutrient digestibility of insect-based diets showed variation within and between studies in weaned piglets and growing pigs. The variability in nutrient digestibility of insect products is mainly due to changes in diet composition when insect products are included. The nutrient digestibility of diets depends on the source of protein that is used or exchanged. Also differences in insect sources used and processing techniques applied may have affected nutrient digestibility in diets. Effects of different insect-based diets on growth performance results were also variable. The effect of insect products on growth performance results is highly dependent on study design, formulation of the diet and the nutritional value of insects adopted during feed formulation. For further studies it is recommended to distinguish studies aimed at determining nutritional value (digestibility studies) and growth performance studies in which the effects of the insect products as dietary ingredient are observed. Health related haematological and biochemical parameters were not affected by dietary inclusion of insect products. In general it can be stated that differences in results between studies may be related to differences in the nature of the insect species, the used substrate to grow the insects and life stages used, in dietary inclusion levels, in the way of processing of the insect products, to variation in palatability of diets, age of the animal and research methods applied. Overall it can be concluded that insect products seem to be a good alternative to partly replace soybean meal or fishmeal in piglet and pig diets without adversely affecting growth performance, product quality and health status. More standardised digestibility and growth performance experiments are recommended for future research and potential positive effects of the use of insect based ingredients on animal health deserve more attention.

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Conflict of interest

The authors declare no conflict of interest.

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