

# The use of black soldier fly (*Hermetia illucens*) larvae meal in pig nutrition

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## REVIEW ARTICLE



### ABSTRACT

Insects are novel and sustainable sources of protein. Black soldier fly larvae (*Hermetia illucens*, BSFL) are the most important farmed insect species. This review focuses on the effects of BSFL meal inclusion on the growth, gut health and immune function of pigs. In all age groups, BSFL meals can support comparable feed intake, nutrient utilisation and growth performance replacing conventional protein sources. The bioactive compounds of BSFL (chitin, lauric acid and antimicrobial peptides) can enhance the health of pigs. Due to the varying origins and chemical compositions of BSFL meals, it is challenging to determine an optimal inclusion level. The application can be especially advantageous in weaned pigs to reduce diarrhoea, in which condition BSFL meal may contribute to decreasing the application of antibiotics. BSFL inclusion may also improve meat quality and carcass yields, but due to higher feed intake, the cost of application is higher for growing and finishing pigs. As BSFL meals have non-standard nutrient content and bioactive compound concentrations, for optimal results, it is advisable to determine the mixing ratio based on the source of the insect meal and the farm conditions.

### KEYWORDS

insects, nutrition, swine, novel protein, functional feed, diarrhoea

## INTRODUCTION

Insects are novel and sustainable protein sources (Oonincx et al., 2010; Veldkamp et al., 2012; Hazcz et al., 2024). Based on their short life cycle, technological requirements and global production rate, black soldier fly larvae (*Hermetia illucens*, BSFL) are the most important farmed insect species (Caparros Megido et al., 2024). BSFL meal is not only a protein source, but it also has special dietary effects due to its chitin, antimicrobial peptide and antimicrobial lauric acid content (Jozefiak et al., 2017; Gasco et al., 2018; Spranghers et al., 2018; DiGiacomo et al., 2019; Wang et al., 2019). Consequently, BSFL meal may improve the gut health and immune function of pigs (Veldkamp and Vernooij, 2021; Hong and Kim, 2022). Based on these physiological effects, BSFL meal inclusion can improve feed efficiency, growth performance, overall health of pigs and decrease the incidence of post-weaning diarrhoea, which may decrease the use of antibiotics (Yu et al., 2020a; Jin et al., 2021; Liu et al., 2023; Phaengphairee et al., 2023).

However, recently, several reviews have been published about the BSFL as animal feed; these do not specifically focus on swine nutrition (Barragan-Fonseca, 2017; Hong et al., 2020; Lu et al., 2022; Seyedalmoosavi et al., 2022; da-Silva et al., 2024; Gautam et al., 2025; Usman Gadzama, 2025; Su et al., 2025). The review by Veldkamp et al. (2021) and Hong and Kim (2022) about the use of insect products in pig diets was not specifically about the BSFL. Since then, new articles have been published, helping the understanding of the dietary effects of BSFL meal on the health of pigs. Our criteria for selecting papers for review were the inclusion of BSFL meal in weaned-, growing-, finishing pigs and sows without additives. *In vitro* BSFL experiments focusing on swine were also involved. Several studies have used other life stages of BSFL, such as prepupae, pupae or BSFL fat; these were not evaluated in

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this paper. The review aims to summarise the effects of BSFL meal inclusion on the growth, gut health, and immune function of pigs. The impact on the performance of the sow and meat quality, as well as the risks and challenges of BSFL meal inclusion, are also discussed.

## NUTRITIONAL COMPOSITION AND BIOACTIVE SUBSTANCES OF BSFL

The nutritional composition of insects is not standard, as the substrate, the life stage as well as the species impact it. Table 1 shows the nutritional composition of BSFL and the other selected farmed insect species. On dry matter basis (DM), the full-fat BSFL typically contains 30–45% crude protein. Due to the nitrogen-containing compounds (e.g., chitin), the true protein level is overestimated by approximately 20% when the conventional 6.25 conversion factor is used to determine the crude protein content. The crude fibre — which refers to chitin as it has a similar structure to cellulose — is 2–9% (Bessa et al., 2020; Thrastardottir et al., 2021; Lu et al., 2022; Zozo et al., 2022). The amino acid (AA) profile is similar to that of fishmeal. Concerning the essential amino acids, BSFL is high in Leu, Lys and Val, while the least abundant are Met and Tryp (Veldkamp and Bosch, 2015; Lu et al., 2022).

The ether extract level is between 25 and 40%. BSFL are high in lauric acid, which typically means 30–40% of the fatty acids (C12:0) but can be lower or higher (~25–60%) depending on the diet (Gasco et al., 2018; Thrastardottir et al., 2021; Lu et al., 2022; Zozo et al., 2022; Suryati et al., 2023; Cattaneo et al., 2023). Lauric acid can also contribute to the energy supply, which is particularly important in piglet nutrition. Among the monounsaturated fatty acids, oleic acid (C18:1; 8–10%) is the most dominant, followed by palmitoleic acid (C16:1; 1.5–6%). Linoleic acid (C18:2n-6) is between 3.5 and 20% and linolenic acid (C18:3n-3, <1–2.5%) content is low (Rabani et al., 2019; Cattaneo et al., 2023), unless the larvae are kept on an omega-3-enriched substrate (Liland et al., 2017; Oonincx et al., 2020). A full-fat BSFL contains approximately 20.6 MJ\*kg<sup>-1</sup> digestible energy and 18.8 MJ\*kg<sup>-1</sup> metabolisable energy for a 25 kg barrow, which is decreased to 16.5 MJ\*kg<sup>-1</sup> digestible

energy and 13.9 MJ\*kg<sup>-1</sup> metabolisable energy in defatted BSFL (Crosbie, 2020).

The bioactive compounds of BSFL meal are chitin, lauric acid and antimicrobial peptides. The exoskeleton of insects has five main layers and is primarily composed of chitin, a polymer formed by a long chain of N-acetyl-β-D-glucosamine joined by 1,4 covalent bonds (Abenaim and Conti, 2025). Undigested chitin is fermented in the large intestine, promoting the growth of beneficial bacteria and increasing short-chain fatty acid (SCFA) production (Rehman et al., 2023; Abenaim and Conti, 2025). Lauric acid is a medium-chain fatty acid with strong antimicrobial activity (Rebucci et al., 2021; Suryati et al., 2023; Macwan et al., 2024). In BSFL, almost sixty peptides with potential antimicrobial, anticancer and antifungal activity have been identified (Moretti et al., 2020). Overall, these bioactive compounds have the potential to enhance the health and productivity of pigs.

## DIGESTIBILITY OF NUTRIENTS IN BSFL-BASED DIETS

Based on *in vitro* measurements, the nutrient digestibility of BSFL can be predicted using the acid detergent fibre (ADF) level. Kim et al. (2023a) evaluated the correlation coefficients between chemical composition and *in vitro* nutrient digestibility of defatted BSFL. The ADF and chitin levels were negatively correlated with *in vitro* ileal digestibility of DM and *in vitro* total tract digestibility of DM and organic matter. The authors made the following prediction equations for *in vitro* nutrient digestibility of BSFL. *In vitro* ileal digestibility of CP (%) =  $-0.95 \times \text{ADF} (\% \text{ DM}) + 95$  ( $r^2 = 0.75$  and  $P = 0.058$ ). *In vitro* total tract digestibility of DM (%) =  $-2.09 \times \text{ADF} + 113$  ( $r^2 = 0.99$  and  $P < 0.001$ ). In an *in vitro* study Oh et al. (2024) concluded that hot-air drying, microwave drying, and freeze drying of full-fat BSFL resulted in comparable and relatively high nutrient digestibility.

Insects are part of the natural diet of pigs; thus, from a young age, pigs have chitinase activity in the stomach (Kawasaki et al., 2021). Liu et al. (2023) reported the same level of acidic mammalian chitinase activity in the stomach, jejunum and ileum independently of the level of insect meal inclusion. This suggests that chitinase activity need not be

Table 1. Nutritional composition of selected farmed insect species (on dry matter basis)

Species	Crude protein	Ether extract	Chitin	Dominant fatty acid (% Total Fatty Acid)	Reference
Black soldier fly larvae	30–45%	25–40%	3–9%	Lauric acid (30–40%), oleic acid (8–10%), linoleic acid (3.5–20%)	Thrastardottir et al. (2021), Rehman et al. (2023), Suryati et al. (2023)
Yellow mealworm larvae ( <i>Tenebrio molitor</i> )	20–50%	20–40%	3–9%	Oleic acid (~45%), linoleic acid (~30%), palmitic acid (~15%)	Thrastardottir et al. (2021), Hong et al. (2020), Rehman et al. (2023), Suryati et al. (2023)
House cricket ( <i>Acheta domestica</i> )	65–70%	15–25%	3–12%	Linoleic acid (~30%), oleic acid (~25%), palmitic acid (~24%)	Thrastardottir et al. (2021), Tzompa-Sosa et al. (2021), Rehman et al. (2023)

induced. Despite chitinase production, a higher inclusion of BSFL, due to its high chitin content, may decrease nutrient digestibility, especially crude protein. Yu et al. (2020a) found that even a low, 4% inclusion rate negatively affected the total tract apparent digestibility of protein in weaned pigs (75.59% vs 71.33%). However, Lee et al. (2024) did not report a decreased crude protein and AA total tract digestibility compared with control diets (5% defatted BSFL inclusion).

The apparent ileal digestibility (AID) and standard ileal digestibility (SID) of AAs, particularly Lys and Met, are generally high (Tansil et al., 2023; >87%; 36.5% partially defatted BSFL meal inclusion). Hosseindoust et al. (2023; 42.76% full-fat BSFL) found the AID of protein (71.6% vs 73.8%), the AID of Arg, His, Leu, Thr and the SID of Arg, His, Ile, and Leu were lower than in the control group. Digestibility does not always equate to metabolic availability (MA). Tansil et al. (2023) evaluated the MA of AAs using the indicator amino acid oxidation technique. They concluded that only ~ half of the Met (one of the first-limiting AAs in BSFL protein for pigs; Veldkamp and Vernooij, 2021) absorbed was available to the pigs, as the SID of Met was ~90.4%, but the MA was ~53.3%. In general, MA < SID for AAs, but such a wide gap was unexpected. This may be explained by the presence of D-Met isomers that are absorbed but not efficiently incorporated into body protein, or the chitin content of BSFL meal affecting Met utilisation. Interpretation of these results is difficult, as none of the other studies measured MA in BSFL-fed pigs. Based on these studies, the SID and the AID of the BSFL diets are comparable with those of the other protein sources used in the control groups.

BSFL-inclusion has little or no effect on the digestibility of DM and organic matter (Biasato et al., 2019; Yu et al., 2020a; Håkenåsen et al., 2021; Kim et al., 2023b; Liu et al., 2023; Lee et al., 2024). Ether extract digestibility can be improved with an increasing inclusion level (Liu et al., 2023; Phaengphairee et al., 2023). The latter can be explained by the high medium-chain fatty acid content of BSFL, resulting in rapid degradation. However, one study reported a decreased ether extract digestibility when BSFL was included in 4% (Yu et al., 2020a; 68.71% vs 65.45%). Most studies concluded that moderate levels of BSFL (up to ~9%) in weanling diets have on adverse effects on the digestibility of these nutrients.

According to Yordanova et al. (2025), the full-fat BSFL (3, 6, 9 and 12%) did not impact the digestibility of crude protein, DM, crude fibre and acid detergent fibre in growing pigs. Fat digestibility was significantly higher in the 9 and 12% inclusion groups compared to the control and linearly increased with the inclusion level. In growing pigs (~25 kg), the SID for most AAs was above 80% (50% of full-fat BSFL or 36.5% of defatted BSFL inclusion; Crosbie et al., 2020). This study concluded that fat extrusion can decrease the SID of certain AAs (e.g., Met, Arg, Val) due to the increased relative chitin/fibre content. The SID of crude protein was not affected. Overall, both full-fat and defatted BSFL meals provided high (80–90%) SID for Lys, Met, Thr, comparable

to many conventional ingredients. Thus, both full-fat and defatted BSFL can be used in growing pig diets without detrimental effects on the digestibility.

Compared to weaned pigs, limited research is available on finishing pigs. Chang et al. (2025) reported increased protein digestibility between weeks 6 and 9 of the study compared with the control group (week 6: 74.6% and 77.54% vs. 72.05%; week 9: 75.31% and 78.33% vs. 70.54%). However, the inclusion rate of defatted BSFL meal was low, only 1 and 2% respectively. Both groups showed higher digestibility of all indispensable AAs than the fish meal-fed pigs at week 6 and 9 (except Arg at week 6). Moreover, at week 6, the 2% group showed higher digestibility of Thr, Val, Ile, Leu, Lys, Arg, and Met than the 1% group. At week 9, the tendency was the same except for all indispensable AAs, except Phe, Arg and Tryp. As a limitation, specific SID/AID values in finishing pigs are not available, but the maintained or even improved performance indirectly proves the good digestibility of AAs. This study did not measure the digestibility of other nutrients and Chia et al. (2021) did not measure protein or AA digestibility; thus, information is limited.

Manufacturing processes may affect protein digestibility. Heat processing (69.6% inclusion of expanded BSFL larvae, a mixture of 50% BSFL and 50% corn flour) can slightly, but not significantly, increase the SID and the AID of AAs compared to full-fat BSFL (Hosseindoust et al., 2023). Heat treatment denatures proteins and makes AAs more accessible to digestive enzymes, thereby enhancing digestibility. Defatting increases the protein concentration (by 15–20%) of BSFL meals while reducing their energy density (~14.5 vs. ~11.0 MJ\*kg<sup>-1</sup>) (Hong and Kim, 2022). The increased relative chitin/fibre content of defatted meals may negatively impact AA digestibility (Crosbie et al., 2020). The digestibility trials with hydrolysed BSFL meal yielded contradictory results. At the 2nd week of the study, the defatted meal (5% inclusion; 80.36%) diet had higher apparent total-tract crude protein digestibility than the hydrolysed meal (5% inclusion; 73.19%; Lee et al., 2024). AA digestibility was not impacted. The authors assumed that the high pressure used for the defatting process could decrease the chitin content and consequently increase the protein digestibility. As chitin levels were not measured, this cannot be proved. Also, this assumption contradicts the negative impact of increased relative chitin/fibre content of defatted meals. As most studies used a full-fat BSFL meal, currently, we have limited information, but manufacturing seems to have little impact on the digestibility.

The contradictory results of weaned pigs concerning the protein digestibility may be explained by the still-developing digestive system and the different origin, inclusion levels and non-standard nutrient content of BSFL meals. The latter involves different concentrations of bioactive compounds, which significantly impact pig health. More studies are needed to evaluate the clear effect on the digestibility. As it will be discussed in the next chapter, BSFL inclusion resulted in comparable feed intake and growth performance as conventional protein sources.

## EFFECTS ON GROWTH PERFORMANCE AND FEED CONVERSION RATIO

It is difficult to fully evaluate the impact of BSFL meal inclusion, as not all digestibility trials measured performance and vice versa. However, Yu et al. (2020a; 4% full-fat BSFL meal) showed that the decreased digestibility of crude protein did not impair growth performance. This may be attributed to the presence of bioactive compounds that positively affect gut health and microbiota. Only two studies examined the effects of insect-based diets (12.5 and 25% defatted BSFL inclusion) in the pre-weaning period and BSFL did not have an impact on the body weight at weaning or overall health (Kawasaki et al., 2023; Zhao et al., 2024). Growth performance in weaned pigs fed BSFL meals has generally been comparable to those fed conventional proteins (Table 1, Boontiam et al., 2022; Kawasaki et al., 2023; Szczepanik et al., 2023; Malla et al., 2024; Zhao et al., 2024). A higher-than-optimal inclusion level may decrease growth performance, primarily due to increased chitin intake and consequently reduced nutrient digestibility (Yu et al., 2020a). As Table 2 shows, pigs generally tolerate BSFL meal inclusions up to ~14%, without adverse effects on average daily gain (ADG), average daily feed intake (ADFI) or feed conversion ratio (FCR), compared to the control diet. In weaned piglets, Yu et al. (2020a), Håkenåsen et al. (2021) and Tang et al. (2022) observed improved ADG during the earlier period (0–14 days), but not for the overall study, which is consistent with the results of Biasato et al. (2019) and Jin et al. (2021). Higher inclusion rates are not commonly observed in studies using weaned pigs; however, according to Håkenåsen et al. (2021), up to 19.06% can be included in these diets without adverse effects. Song et al. (2024) also concluded that defatted BSFL can fully replace other protein sources without negative effects in nursery pigs (full-fat BSFL up to 20% and defatted BSFL up to 30% inclusion). BSFL can be introduced in grower diets without a negative impact on performance up to 18.5% (Chia et al., 2019; Chang et al., 2025; Yor). As Table 2 shows, the FCR of BSFL-fed weaned and growing pigs is equivalent to that of control diets, and a higher insect-meal inclusion level also did not have a significant effect on the measured parameters.

Zhu et al. (2022) reached a higher ADG in the 8% BSFL group than in the control, but there was no difference in the final body weight in finishing pigs. Chia et al. (2021) also reported an increase in ADG and better FCR (9, 12, 14% inclusion full-fat BSFL) compared with the control fishmeal diet. Consequently, BSFL can completely replace fishmeal in the diet of finishing pigs. Table 2 shows that finishing pigs have equal or better performance on BSFL-inclusive diets than on control diets. The better tolerance of higher BSFL meal inclusion levels (up to 14%) of fattening pigs compared with weaned pigs might be explained by the more developed digestive system and greater hindgut fermentation capacity to deal with chitin.

## EFFECTS ON GUT HEALTH, IMMUNE FUNCTION AND OXIDATIVE STRESS

Beyond nutritional benefits, BSFL meals offer antimicrobial and immunomodulatory functional properties, including chitin, lauric acid and antimicrobial peptides, which contribute to improved gut health (Wan et al., 2017; Zong et al., 2020; Rebutti et al., 2021; Adli et al., 2022; Liu et al., 2023). As Table 3 shows, the minority of studies showed increased villi height, decreased crypt depth and improved villus height and crypt depth ratio (VH: CD) in the duodenum, jejunum and ileum. Overall, in weaned pigs, moderate levels of BSFL do not have a significantly positive impact on the intestinal morphology. On the other hand, a higher inclusion level (18.3% vs 4.5%) of full-fat BSFL can significantly decrease VH:CD in the duodenum and jejunum (Liu, 2023) that play a key role in nutrient absorption. Fewer studies are available on growing pigs, suggesting that BSFL meal does not significantly enhance or worsen intestinal villus architecture, even at high inclusion levels (18.5% BSFL; Chia et al., 2019). This may be explained by the more developed gastrointestinal tract and less sensitivity to dietary changes in the morphology of older pigs compared to weaned pigs.

BSFL inclusion tends to increase beneficial *Lactobacillus* and *Bifidobacterium*, while suppressing potential pathogens like *E. coli* in the small intestine of weaned pigs (Boontiam et al., 2022; Tang et al., 2022; Phaengphairee et al., 2023). *Streptococcaceae* and *Staphylococcaceae* can also be decreased (Jin et al., 2021). At the phylum level, enhanced *Firmicutes* is an advantageous example enhanced by BSFL inclusion (Yu et al., 2020b; Jin et al., 2021). In the colon, SCFA-producing genera (e.g. *Lactobacillus reuteri*, *Faecalibacterium*) are enhanced and microbial diversity is also improved, resulting in increased fermentative metabolites, such as butyrate (Yu et al., 2020b; Jin et al., 2021; Boontiam et al., 2022; Tang et al., 2022; Zhao et al., 2024). However, not all studies reported altered SCFA concentrations in the colon (Håkenåsen et al., 2021; Liu et al., 2023; Malla et al., 2024; Zhao et al., 2024). Overall, in weaned and growing pigs, BSFL inclusion leads to a higher abundance of beneficial bacteria without causing an inflammatory reaction or overgrowth of pathogenic bacteria (Biasato et al., 2023; Kar et al., 2021; Zhao et al., 2024). In finishing pigs, BSFL meal increased the colonic counts of *Lactobacillus*, *Roseburia* and *Faecalibacterium* at a 4% inclusion rate and decreased the counts of *Streptococcus* and protein-fermenting microbes. Consequently, the concentration of SCFAs, especially of butyrate, increased in the colon (Yu et al., 2019).

The potentially positive effects on gut health, such as improved gut morphology, strengthened intestinal barrier function and microbiota, are especially important in decreasing the incidence or the severity of post-weaning diarrhoea. Several studies reported reduced incidence of diarrhoea in BSFL-fed weaned pigs (Yu et al., 2020a, 2% full-fat BSFL; Phaengphairee et al., 2023, 12% full-fat BSFL; Boontiam et al., 2022, 6 and 12% full-fat BSFL).

Table 2. Effects of black soldier fly larvae meal inclusion (as fed basis) on the growth performance of pigs for the overall feeding period compared to the control diet

BSFL inclusion	Pigs and study length	Main outcomes	References
5 and 10% partially defatted BSFL	IBW: 6.1 ± 0.2 kg WP; 40-day long	Both groups: ADG, ADFI and FCR ↔	Biasato et al. (2019)
1, 2 and 4% full-fat BSFL	IBW: 7.9 ± 0.4 kg WP; 28-day long	All groups: ADG, ADFI and FCR ↔	Yu et al. (2020a)
4 and 8% full-fat BSFL; ETEC challenged pigs	IBW: 7.7 ± 0.3 kg WP; 28-day long	Both groups: ADG, ADFI and FCR ↔	Jin et al. (2021)
4.76, 9.52 and 19.06% full-fat BSFL	IBW: 10.6 ± 0.8 kg WP; 28-day long	All groups: ADG, ADFI and FCR ↔	Håkenåsen et al. (2021)
7.38%/3.75%/0.5% full-fat BSFL and 14.76%/7.5%/1% full-fat BSFL	IBW: 6.7 ± 0.2 kg WP; 21-day long	All groups: ADG, FCR ↔	Crosbie et al. (2021)
6 and 12% full-fat BSFL	IBW: 7.4 ± 0.2 kg WP; 28-day long	Both groups: ADG, ADFI and FCR ↔	Boontiam et al. (2022)
3% full-fat BSFL; ETEC-challenged pigs	IBW: 8.4 ± 0.0 kg; 28-day long	ADG, ADFI and FCR ↔	Tang et al. (2022)
4.5, 9.1, 13.7 and 18.3% full-fat BSFL	IBW: 7.4 ± 0.8 kg WP; 28-day long	All groups: ADG ↑, FCR ↔; 4.5%, 9.1%: ADFI ↑	Liu et al. (2023)
12% full-fat BSFL	IBW: 7.3 ± 0.2 kg WP; 28-day long	ADG, ADFI and FCR ↔	Phaengphairee et al. (2023)
pre-weaning: 12.5 and 25% defatted BSFL	IBW (12.5%): 7.5 ± 0.5 kg	All groups: ADG, ADFI and FCR ↔	Kawasaki et al. (2023)
post-weaning: 4 and 8% defatted BSFL	IBW (25%): 5.7 ± 0.2 kg WP pre-weaning diet: day 21–35 post-weaning diet: day 35–63		
30% full-fat BSFL	IBW: 6.9 ± 0.2 kg WP, 42-day long	ADG, ADFI and FCR ↔	Christensen et al. (2023)
2.5, 5% full-fat BSFL	IBW: 8.7 ± 0.2 kg WP; 35-day long	All groups: ADG, ADFI and FCR ↔	Szczepanik et al. (2023)
4, 8% full-fat BSFL	IBW: ~7.5 kg WP-GP; 114 day-long	ADG ↑ (8%),	Zhu et al. (2022)
12.5 and 25% defatted BSFL	IBW (12.5%): 6.5 ± 0.4 kg IBW (25%): 5.4 ± 0.4 kg WP; 14-day long	All groups: ADG, ADFI and FCR ↔	Zhao et al. (2024)
8.35% defatted BSFL	IBW: 6.6 ± 0.5 kg WP; 14 day-long	ADG, ADFI and FCR ↔	Malla et al. (2024)
5% defatted and 5% hydrolysed BSFL	defatted BSFL IBW: 6.7 ± 0.7 kg WP hydrolysed BSFL IBW: 8.2 ± 0.4 kg 48 day-long	Defatted BSFL: ADG ↑, ADFI ↔, FCR ↓ hydrolysed BSFL: ADG, ADFI and FCR ↔	Lee et al. (2024)
9, 12, 14.5 and 18.5% full-fat BSFL	IBW: 18.2 ± 0.3 kg GP; 9-week long	All groups: ADG, FCR ↔	Chia et al. (2019)
1, 2% defatted BSFL	IBW: 34.8 ± 0.4 kg GP-FP; 9-week-long	ADG, ADFI and FCR ↔	Chang et al. (2025)
3, 6, 9, 12% full-fat BSFL	IBW: 31.8 ± 0.1 kg GP; 38-day long	ADG, ADFI and FCR ↔	Yordanova et al. (2025)
6, 9, 12, 14% full-fat BSFL	IBW: 54.3 ± 0.9 kg FP; 14 week-long	ADG ↑ (9%, 12%, 14%), ADFI ↔, FCR ↓ (9%, 12%, 14%),	Chia et al. (2021)

BSFL = black soldier fly larvae, IBW = initial body weight, WP = weaned pigs, GP = growing pig, FP = finishing pig, ADG = average daily gain, ADFI = average daily feed intake, FCR = feed conversion ratio, ETEC = enterotoxigenic *Escherichia coli*.

Liu et al. (2023) only reported decreased incidence of diarrhoea in the 18.3% BSFL group; lower inclusion rates were not efficient. BSFL meal also reduced enterotoxigenic *Escherichia coli*-induced diarrhoea in weaned piglets and may be an effective strategy to replace antibiotics (Jin et al., 2021; Tang et al., 2022; Phaengphairee et al., 2023). In piglets, a BSFL-based diet can modulate mucosal immunity toward an anti-inflammatory profile. BSFL meals may modulate gene expression related to immune responses.

As Table 4 shows, several studies have reported the downregulation of pro-inflammatory gene expressions in the small intestine (e.g., TLR4, MyD88, NF-κB, and TNF-α). Humoral immunity can also be enhanced, marked by elevated plasma immunoglobulins (e.g., IgA and IgG), anti-inflammatory cytokines (e.g., IL-10) and reduced plasma levels of pro-inflammatory cytokines (IL-1β, IL-6, and TNF-α). Several studies have reported a strengthened intestinal barrier function, marked by the upregulation of tight

Table 3. Effects of black soldier fly larvae meal inclusion (as fed basis) on the intestinal morphology in weaned piglets compared to the control diet

BSFL inclusion	Duodenum	Jejunum	Ileum	Reference
	Villus height, crypt depth, villus:crypt ratio			
12% full-fat BSFL	↑, ↔, ↑	↔, ↔, ↔	↔, ↔, ↔	Phaengphairee et al. (2023)
3% full-fat BSFL; ETEC-challenged pigs	NA	↑, ↓, ↑	↔, ↔, ↔	Tang et al. (2022)
4 and 8% full-fat BSFL; ETEC challenge pigs	NA	NA	4%: ↑, ↔, ↑ 8%: ↑, ↔, ↑	Jin et al. (2021)
4.5 and 18.3% full-fat BSFL	4.5%: ↔, ↔, ↑ 18.3%: ↔, ↔, ↔	4.5%: ↔, ↔, ↔ 18.3%: ↔, ↔, ↔	4.5%: ↔, ↔, ↔ 18.3%: ↔, ↔, ↔	Liu et al. (2023)
5 and 10% partially defatted BSFL	5%: ↔, ↔, ↔ 10%: ↔, ↔, ↔	5%: ↔, ↔, ↔ 10%: ↔, ↔, ↔	5%: ↔, ↔, ↔ 10%: ↔, ↔, ↔	Biasato et al. (2019)
1, 2 and 4% full-fat BSFL	NA	1%: ↔, ↔, ↔ 2%: ↑, ↔, ↔ 4%: ↑, ↔, ↔	1%: ↔, ↔, ↔ 2%: ↔, ↔, ↔ 4%: ↔, ↔, ↔	Yu et al. (2020a)
7.38%/3.75%/0.5% full-fat BSFL and 14.76%/7.5%/1% full-fat BSFL	NA	7.38%/3.75%/0.5%: ↔, ↔, ↔ ↔ 14.76%/7.5%/1%: ↔, ↔, ↔ ↔	7.38%/3.75%/0.5%: ↔, ↔, ↔ ↔ 14.76%/7.5%/1%: ↔, ↔, ↔ ↔	Crosbie et al. (2021)
4.76, 9.52 and 19.06% full-fat BSFL	NA	4.76%: ↔, ↔, ↔ 9.52%: ↔, ↔, ↔ 19.06%: ↔, ↔, ↔	4.76%: ↔, ↔, ↔ 9.52%: ↔, ↔, ↔ 19.06%: ↔, ↔, ↔	Håkenåsen et al. (2021)
6 and 12% full-fat BSFL	6%: ↔, ↔, ↔ 12%: ↔, ↔, ↔	6%: ↔, ↔, ↔ 12%: ↔, ↔, ↔	6%: ↔, ↔, ↔ 12%: ↔, ↔, ↔	Boontinam et al. (2022)
pre-weaning diet: 12.5 and 25% defatted BSFL	12.5%: ↔, ↑ ↔	12.5%: ↔, ↔, ↔	12.5%: ↔, ↔, ↔	Kawasaki et al. (2023)
post-weaning diet: 4 and 8% defatted BSFL	25%: ↔, ↑, ↔ 4%: ↔, ↔, ↔ 8%: ↔, ↔, ↔	25%: ↔, ↔, ↔ 4%: ↔, ↔, ↔ 8%: ↑, ↔, ↔	25%: ↔, ↔, ↔ 4%: ↔, ↔, ↔ 8%: ↔, ↔, ↔	

NA = not available, ETEC = enterotoxigenic *Escherichia coli*.

junction proteins (e.g., Claudin-1, Occludin, ZO-1) and mucins (MUC1, MUC2) (Yu et al., 2020b; Jin et al., 2021; Tang et al., 2022). Increased neutral mucin production was also reported by Biasato et al. (2020). Tang et al. (2022) found a higher number of mucin-producing goblet cells and higher sIgA production. These immunological responses suggest that BSFL may serve as prebiotic or immune-supporting agents in weaned pigs. On the contrary, in the study of Malla et al. (2024; 8.35% defatted BSFL), BSFL did not improve the intestinal mucosa barrier function. This might be explained by the different physiological effects of defatted meal vs. full-fat meal. In finishing pigs, similar to weaned pigs, BSFL meal increased the mucosal gene expression of tight junctions (ZO-1, Occludin) and MUC1 and morphological changes were not detected (Yu et al., 2019). Overall, BSFL meal has little impact on the gut morphology, but has the potential to significantly improve gut microbiota composition, gut barrier function and immune response.

Oxidative stress biomarkers were measured in several studies and among these, the key enzymatic antioxidants are superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPx), while an important oxidative damage indicator is malondialdehyde (MDA) (Durand et al., 2022). Enhanced antioxidant capacity marked by reduced

MDA, increased GPx and SOD activity was reported in BSFL-fed weaned pigs (Phaengphairee et al., 2023; Boontinam et al., 2022). A significantly increased activity of GPx and CAT was also recorded in enterotoxigenic *Escherichia coli*-challenged pigs compared to the control group (Jin et al., 2021). The antioxidant effects of BSFL may also stem from its bioactive components, such as chitin, antimicrobial peptides and lauric acid. However, high inclusion rates (12% in growing pigs) may provoke some oxidative stress, evidenced by rising MDA and decreasing CAT and GPx compared to the control (Yordanova et al., 2025).

## CARCASS TRAITS AND MEAT QUALITY

Altmann et al. (2019) evaluated partially defatted BSFL meal in a three-phase feeding program for grower-finisher pigs. They used BSFL to replace 50–75% (phase 1: 8.1 and 12.5%; phase 2: 6.6 and 9.7% inclusion) of soybean meal in grower feed and up to 100% in late finisher feed (>75 kg body weight; 9.5% inclusion). By sensory analysis of the pork, the overall odour increased and juiciness improved; the physicochemical parameters remained unchanged compared to the control group. The lauric acid content of the backfat of the

Table 4. Effects of black soldier fly larvae meal inclusion (as fed basis) on the gut barrier function and immune response of pigs compared to the control diet

BSFL inclusion	Main effects on gut barrier function	Immune response	Reference
1, 2 and 4% full-fat BSFL	improved gut barrier: ZO-1, Occludin, Claudin-2, MUC1 ↑	mRNA expression in the ileum: 2%: TNF- $\alpha$ , TLR4, MyD88, NF $\kappa$ B ↓; 2% and 4%: IL-10, MUC1, ZO-1, Occludin, Claudin-2 ↑ All groups: ileal mucosa IgA ↑, IgG ↔	Yu et al. (2020b)
4 and 8% full-fat BSFL; ETEC challenge pigs	improved gut barrier in both groups: Occludin in the jejunum ↑; Occludin, and claudin-3 in the ileum ↑; 4%: Occludin, claudin-3, and ZO-1 in the colon ↑. 8%: Occludin in the colon ↑	Both groups: jejunum, ileum, and colon IL-10 ↑; TNF- $\alpha$ in the jejunum and colon ↓; 4%: serum IgG and IgA ↑	Jin et al. (2021)
3% full-fat BSFL; ETEC-challenged pigs	improved gut barrier: Claudin-1, Occludin, MUC1, MUC2 ↑; goblet cell density and secretory	IL-1 $\beta$ , IL-8 in jejunum ↓; IL-10, TGF- $\beta$ in ileum ↑; TLR2, p-NF $\kappa$ B, p-MAPK ↓; IgA in intestine ↑;	Tang et al. (2022)
8.35% full-fat BSFL	plasma D-lactate and diamine oxidase ↔	IgA in the jejunum ↔	Malla et al. (2024)
4.5 and 18.3% full-fat BSFL	Occludin, Claudin-1 and ZO-1 in the ileum ↔	both groups: serum IgA ↔; 4.5%: IgG and IgM ↑	Liu et al. (2023)
12% full-fat BSFL	NA	serum: IgA ↑; IgG ↔, IL-1 $\beta$ ↓; IL-6 and TNF- $\alpha$ ↔	Phaengphairee et al. (2023)

NA = not available, ETEC = enterotoxigenic *Escherichia coli*.

insect-fed group was five times higher than in the control group. The flavour enhancement might be linked to the altered intramuscular fat composition. In contrast to this study, Chia et al. (2021) reported heavier carcasses at slaughter in pigs fed on a BSFL meal diet (9, 12 and 14% inclusion). The diet did not affect the dressed percentage or the loin eye area. The BSFL diet resulted in higher protein (12 and 14% inclusion) and fat contents (6, 9, 12, 14% inclusion) of the loin muscle. At higher inclusion rates, primal cuts (belly, ham and loin) weighed significantly more. Thus, BSFL can be a good alternative to fishmeal and can replace 50–100%. According to Zhu et al. (2022), the inclusion of BSFL meal can significantly improve meat quality. The 4 and 8% insect meal increased the intramuscular fat content, which is one of the important traits of pork quality. As another advantage, drip loss decreased, while marbling scores, shear force, and cooking loss remained unchanged. These studies concluded that adding BSFL to finishing pig feed could improve specific pork quality parameters without detrimental effects on meat quality.

## REPRODUCTIVE PERFORMANCE OF SOWS

Recent studies indicate that incorporating BSFL meal into sow diets does not harm reproductive outcomes. The 2.3 and 4.6% defatted BSFL meal inclusion resulted in similar litter sizes, body weight at birth and weaning and weaning rate than in the control group (Kawasaki et al., 2023).

Haematology and plasma biochemistry parameters in sows were within physiological limits, indicating metabolic health. With one exception, these inclusions did not have an impact on the DM, crude protein, crude fat and crude ash content of sow milk (within 24 h of parturition, 7 days after parturition, 28 days after parturition). The DM was significantly higher on day 28 in the 2.3% BSFL meal group. The sows' milk did not affect the pre-weaning performance of piglets (Zhao et al., 2024). As both inclusion levels were low and the meal was defatted, more studies are needed to evaluate the impact of BSFL meal on sows' performance and milk quality, especially fatty acid composition.

## LEGAL FRAMEWORK, SAFETY AND CHALLENGES

Currently, in the European Union, insects and their derived products used as animal feed are considered animal by-products (Regulations No 999/2001 and 1069/2009). Black soldier fly processed animal protein (PAP) is authorised in feeds for swine (Regulation No 999/2001 and 2017/893; Meijer et al., 2025). In the USA, whole-dried BSFL and BSFL meal are also authorised for swine, while they are not allowed in Canada and Australia. In several countries, such as China and South Korea, there is no specific law regulating the use of insects as animal feed (Zou et al., 2024).

The most significant safety concerns for insect-based meals are the presence of heavy metals, pesticides,

mycotoxins and microbiological risks, including bacteria (such as *Salmonella* and *Escherichia coli*), viruses and parasites (Diener et al., 2015; Macwan et al., 2024; Alejandro et al., 2025; Ankowski et al., 2025; Gautam et al., 2025; Rossi et al., 2025). In countries where substrate quality is strictly controlled and regulated, high-risk organic wastes (e.g., manure, catering waste) are not authorised as substrates. Consequently, most of these risks can be eliminated. Also, PAPs must comply with the European Union's hygiene regulations. This process involves heat treatment, eliminating the potential microbiological risks (Regulation No 142/2011).

Challenges include a lack of data on the optimal inclusion level by age and BSFL meal type (i.e., full-fat, partly defatted, or defatted). Concerning practical application, another hindering factor is the high cost of BSFL production, which consequently results in a high price for BSFL meal. In the simulation of Leipertz et al. (2024a), the price of the defatted BSFL meal was €5,116\*t<sup>-1</sup> DM. To become price competitive in broiler production, it should cost 801 €\*t<sup>-1</sup> DM. A 10% inclusion of defatted BSFL meal would increase broiler breast meat by 53.7% (Leipertz et al., 2024b). Swine-specific calculations have not been made, but presumably, conclusions would be similar. The number of commercial insect farms is increasing, but insect meals still face supply chain limitations. Consumers' aversion and social and cultural challenges can be mentioned as well. Nutritional variability in BSFL meals is of great importance, influencing physiological effects in pigs. Both macro- and micronutrients, as well as bioactive compounds, show significant variability depending on substrate composition and manufacturing (Raman et al., 2022; Macwan et al., 2024; Gautam et al., 2025; Rossi et al., 2025).

## CONCLUSIONS

BSFL meals can support comparable feed intake, nutrient utilisation and growth performance when replacing conventional protein sources. Most of the studies concluded that the BSFL inclusion does not have a significantly positive impact on the performance and gut morphology. However, the insect meal can improve gut microbiota composition (by increasing *Lactobacillus* and *Bifidobacterium*, while suppressing potential pathogens like *Escherichia coli*), gut barrier function and immune response. These are especially important in weaned pigs to decrease the risk of post-weaning diarrhoea. Due to the varying origins and chemical compositions of BSFL meals, it is challenging to determine an optimal inclusion level. In weaned pigs, too high inclusion (>12%) may have adverse effects on gut morphology and too low (<4% full-fat BSFL) inclusion may not have any significantly positive impact on the performance or gut health of pigs. The application can be especially beneficial in weaned pigs to reduce diarrhoea, in which BSFL meal may contribute to the decreased application of antibiotics. For growing pigs, the advantages of BSFL compared to conventional protein sources are smaller and due to higher feed

intake, the cost of application is higher. Here, the inclusion of full-fat BSFL can be up to ~18%. Finishing pigs show equal or better performance on BSFL-inclusive diets than on control diets without negatively impacting the meat quality. Carcass yields can be improved, making BSFL a promising protein alternative for finishing pigs in up to 14% inclusion. Concerning sows, there is not enough information to conclude. Complex studies, examining all aspects of BSFL inclusion (digestibility, performance, gut microbiota, gut morphology and meat quality) could help to make stronger evidence concerning the impact of BSFL meal in pig production and health. Because BSFL meals have non-standard nutrient content and bioactive compound concentrations, for optimal results, it is advisable to determine the mixing ratio based on the source of the insect meal and the farm conditions.

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