



INFLUENCE OF FEEDING BLACK SOLDIER FLY (*HERMETIA ILLUCENS*) LARVAE PROTEIN MEAL ON CARCASS CHARACTERISTICS AND MEAT QUALITY IN GROWING-FINISHING PIGS

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Abstract

One of the priorities of modern agricultural science is the transition to highly productive and environmentally friendly animal husbandry. The search for alternative protein sources to replace imported soybean meal and fishmeal is crucial for ensuring food security. This study evaluates the effect of including protein meal from black soldier fly (*Hermetia illucens*) larvae in pig diets on growth performance, slaughter indicators, and qualitative parameters of pork. The experiment was conducted on 24 pigs divided into four groups: a control group (C) fed standard compound feed containing fishmeal, and three experimental groups with partial or complete replacement of fishmeal by insect meal during the growing-finishing period. Groups E1, E2, and E3 received a one-third, a two-third and a full replacement of fishmeal with black soldier fly larvae meal (BSFLM), respectively. Over the 97 days, all experimental groups demonstrated superior growth performance compared to the control. The highest average daily gain (ADG) was recorded in Group E3 (1038.16 g/day), exceeding the control by 5.37%. Feed conversion ratio (FCR) improved significantly across all test groups; the most efficient result was observed in Group E1 (2.71 kg/kg), which was 9.1% better than the control ($p = 0.10$). Slaughter analysis revealed a positive trend in carcass traits. Pigs from Group E3 achieved the highest hot carcass weight (85.49 ± 2.54 kg) and dressing percentage ($74.30 \pm 0.23\%$). Meat quality assessment indicated an improvement in water-holding capacity (WHC) and muscle fiber characteristics. Notably, there was a statistically significant reduction in fat content in Groups E2 (22.99%) and E3 (22.85%) compared to the control (23.42%, $p = 0.03$), alongside an increase in crude protein levels in Group E1 (72.09%, $p < 0.05$). Evaluation of meat quality showed higher pH values at 45 minutes post-slaughter in the experimental groups, contributing to improved technological properties of the meat. Thus, replacing traditional animal proteins with *Hermetia illucens* larvae meal not only serves as an eco-friendly alternative but also enhances the efficiency of pork production, improving specific nutritional and technological qualities of the final product without compromising animal health or growth rates.

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Introduction

Researchers predict that global consumption of pork and poultry meat will increase in the next 5–7 years to 127 million tons and 145 million tons, respectively. At the same time, one of the most significant social challenges currently is the need to increase food production while reducing its negative environmental effects without increasing costs. Meat production requires feeding animals with grains and soybean meal, which are the main sources of energy and crude protein. The dependence of monogastric animals on these feed crops has become problematic due to food competition [1,2].

Recently, entomophagy (the consumption of eggs, larvae, pupae, and adult individuals of certain insect

species) has attracted considerable attention as a potential nutritional source for the future within a sustainable food system [3,4]. Extracted insect proteins are used in feeds for livestock and poultry. The primary advantages of this approach include their status as a highly nutritious source rich in fat, protein, vitamins, fiber, and minerals [5,6].

Compared to other animal-derived protein sources, insects require significantly less water and space for cultivation, produce comparatively low amounts of greenhouse gas emissions, exert limited pressure on natural resources, and can be efficiently utilized in an animal protein production system [6,7].

In this context, the black soldier fly (*Hermetia illucens*) larva is considered the most promising candidate for providing high-quality nutritious feed for animals and poultry [8]. Their nutritional composition may vary depending on the rearing substrate, but their bodies contain approximately 40 % protein and 30 % fat [9,10]. Due to the fact that the black soldier fly larva is rich in protein and fat, diets containing it are a valuable source of feed [11,12]. The black soldier fly contains high levels of microelements such as calcium, zinc, potassium, iron, manganese, and phosphorus [13], as well as antibacterial substances like antimicrobial peptides [14,15].

It has also been noted that the content of crude fat, crude protein, and ash differs across various developmental stages of the black soldier fly [10,16]. Crude fat content may be closely related to the percentage of “identified fatty acids” within them, as the fraction termed “crude fat” mainly consists of fatty acids. In terms of protein and fatty acid content, the insect’s composition is comparable to soybean meal and soybean oil [15]. Many researchers have used black soldier fly larvae in powder or fat form as a protein or fat source to partially replace corn, soybean meal, and soybean oil, or by feeding the larvae themselves as animal feed.

The use of black soldier fly larvae in the diets of farm animals and poultry can take the form of whole insects (dried or live), as well as derived ingredients: meals (partially defatted) and oils [17]. The protein obtained from this insect is rich in essential amino acids, which determines the superiority of such feed compared to soybean meal in terms of amino acid composition [18]. Meal and oil can serve as effective substitutes for protein and energy sources, including soybean meal and oil, fish meal, and meat-and-bone meal [19]. In terms of protein quality, *Hermetia illucens* larvae contain more essential amino acids than fishmeal and less than soybean meal [20]. Insect-derived diet ingredients are rich in protein and fat and can be used as a food source for almost all animal species and at different ages [21].

In pig diets, conventional feeds can be replaced with insect products, considering that pigs are omnivores. Replacing traditional feeds with co-product-based ingredients in swine diets is a key strategy for enhancing the sustainability of pig farming [22].

A substantial body of research regarding the use of black soldier fly larvae meal in commercial feeds has been presented for chickens. Thus, egg production and meat quality were studied in White Leghorn chickens fed defatted insect meal (7.5 %) and corn-soybean meal [23], the effect of dietary replacement of soybean and fish meal with black soldier fly meal on broiler growth and economic indicators of poultry farming [24,25], the economic efficiency of using insect meal as a substitute for fish meal in diets for breeding hens and roosters [26], as well as the effect of diets containing black soldier fly larvae on meat and egg

quality indicators in poultry [27] and pigs, for example, improving pork quality when using insect protein in their diets [28], the effect of replacing fish meal with insect meal on growth performance, blood profiles and economic indicators of animal rearing [29], changes in intestinal microbiota when feeding diets containing black soldier fly larvae with replacement soybean meal in growing pigs [30,31] and meat quality [32].

An improvement in broiler growth performance was observed when using dried larvae in powder form, alongside an increase in saturated fatty acid content in their meat [25,33,34]. Using black soldier fly meal as a protein source for laying hens may improve egg quality [35,36]. Studies were conducted on the partial replacement of soybean meal and soybean oil with defatted fly larvae in quail diets, noting improvements in the quality of their meat and eggs when fed such a diet [17].

Several studies have been conducted on the use of the black soldier fly in finishing pig diets. Specific nutritional properties of the larvae affect animal health and can control gut microbiota [37,38]; furthermore, their inclusion influences meat quality (intramuscular fat content and other indicators) [39]. Zhu et al. [40] found that feeding black soldier flies in diets for finishing pigs led to an increase in intramuscular fat, but the reasons for these changes were not examined. There is still insufficient information regarding the influence of black soldier fly larval feedstuffs on the productivity of finishing pigs and product quality [41].

The aim of the present research was to study the replacement of traditionally used fish meal with black soldier fly larvae meal. The objective was to evaluate the effect of this substitution on the growth and productivity of modern genotype pigs, as well as the composition and quality of the resulting products.

Objects and methods

The experiment was conducted on 24 barrows (F-2: ((Large White × Landrace) × Duroc)) with a live weight of 28.25 ± 0.59 kg at the age of 77 days, under the conditions of a physiological yard and in the laboratories of the L. K. Ernst Federal Research Center for Animal Husbandry. The animals were divided into 4 groups. Based on the nutritional data of basic feeds, animal requirements, as well as the nutritional value of fish meal (FM) and black soldier fly larvae meal (BSFLM), an animal feeding scheme was developed. Group E1: partial replacement (1/3 FM with BSFLM), Group E2: more significant replacement (2/3 FM with BSFLM), Group E3: complete replacement of FM with BSFLM, C: control group. A detailed research scheme considering the experimental periods is presented in Table 1.

The composition of the compound feeds used to feed pigs during the study can be found in the data provided in Table 2.

Table 1. Experimental design

Groups	Number of animals	Feeding characteristics
Growing phase — 30 days		
Control (C)	6	Swine compound feed (SK-4) containing 7.5 % fish meal (FM)
Exp. 1 (E1)	6	SK-4 with 5 % FM and 3 % black soldier fly larvae meal (BSFLM)
Exp. 2 (E2)	6	SK-4 with 2.5 % FM and 6 % BSFLM
Exp. 3 (E3)	6	SK-4 with 9 % BSFLM
1st Fattening period — 31 days		
Control (C)	6	Swine compound feed (SK-5) containing 2.76 % FM
Exp. 1 (E1)	6	SK-5 with 1.84 % FM and 1 % BSFLM
Exp. 2 (E2)	6	SK-5 with 0.92 % FM and 2 % BSFLM
Exp. 3 (E3)	6	SK-5 with 3 % BSFLM
2nd Fattening period — 26 days		
Control (C)	6	Swine compound feed (SK-6) containing 0.9 % FM
Exp. 1 (E1)	6	SK-6 with 0.6 % FM and 0.33 % BSFLM
Exp. 2 (E2)	6	SK-6 with 0.3 % FM and 0.66 % BSFLM
Exp. 3 (E3)	6	SK-6 with 1 % BSFLM

Table 2. Composition of compound feeds for growing-fattening young pigs by periods

Component, %	Feed Designation		
	SK-4 ¹	SK-5 ²	SK-6 ³
Wheat	46.40	49.99	40.00
Barley	28.45	31.43	19.16
Corn	—	—	15.00
Soybean meal, CP 44 %	10.87	—	3.00
Sunflower meal, CP 36 %	2.50	8.35	9.00
Dried distillers grains	—	4.00	—
Peas	—	—	1.50
Fish meal	7.50	2.76	0.90
Wheat bran	—	—	8.40
Salt	0.50	0.50	0.50
Lysine sulfate	0.78	1.12	0.63
Methionine	0.13	0.02	—
L-Threonine	0.17	0.06	0.05
Monocalcium phosphate	0.46	0.28	—
Limestone flour	0.94	1.19	1.36
Premix	0.30	0.30	0.30

Note: ¹ Feed for growing; ² Feed for 1st fattening period; ³ Feed for 2nd fattening period.

The control group (C) received compound feeds without the inclusion of additional feedstuffs. For groups E1, E2, and E3, partial (1/3 and 2/3) and complete replacement of FM was performed:

1. During growing: E1–5 % FM and 3 % BSFLM; E2–2.5 % FM and 6 % BSFLM; E3–9 % BSFLM;
2. During 1st fattening: E1–1.84 % FM and 1 % BSFLM; E2–0.92 % FM and 2 % BSFLM; E3–3 % BSFLM;
3. During 2nd fattening: E1–0.6 % FM and 0.33 % BSFLM; E2–0.3 % FM and 0.66 % BSFLM; E3–1 % BSFLM.

The total duration of the experiment was 97. The experiments were carried out in accordance with the requirements of the Federal Law of the Russian Federation¹, the Declaration of Helsinki², the European Convention for the

Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes³.

The studies were conducted in a specialized production facility equipped with all necessary tools and equipment for feed distribution. Animals were housed in pens (4.60 × 2.50 m), 6 heads per pen, equipped with control fattening stations (COMPIDENT MLP 2 PRO station for monitoring fattening performance, SCHAUER AGROTRONIC LLC, Russia) and automatic feed intake accounting (Farm Manager software for the MLP module). Housing conditions ensured constant access to a complete diet and drinking water throughout the entire experimental period. Animal care and housing conditions strictly complied with established norms — temperature regime, humidity, lighting, and air exchange were maintained within veterinary and hygiene requirements. Controlled indicators of feed and component nutrition were determined in the chemical laboratory of the Department of Physiology and Biochemistry of Farm Animals at the L. K. Ernst Federal Research Center for Animal Husbandry.

Individual records of growth rates and feed consumption were kept during the experimental period. To determine live weight gains (absolute gain (AG, g) and average daily gain (ADG, g)), individual weighing of animals was carried out every ten days (in the morning hours) using electronic scales (Schauer Compident MLP II PRO, Austria) integrated into the general data recording system. Feed conversion ratio (FCR) was calculated by dividing Total feed consumed (kg) / Live weight gain (kg).

Control slaughter of the entire livestock ($n = 24$) was performed at the end of the experiment. Determination of live weight before slaughter, carcass weight, backfat thickness, and dressing percentage (ratio of carcass weight to live weight before slaughter) was carried out in accordance with the “Rules for Veterinary Inspection of Slaughter

¹ Federal Law of the Russian Federation dated December 27, 2018 No. 498FZ “On the responsible treatment of animals and on amendments to certain legislative acts of the Russian Federation.” Retrieved from <https://docs.cntd.ru/document/552045936>. Accessed May 19, 2026 (In Russian)

² WMA Declaration of Helsinki - ethical principles for medical research involving human subjects Retrieved from <https://www.wma.net/policiespost/wma-declaration-of-helsinki-ethical-principles-for-medical-research-involving-human-subjects/> Accessed May 19, 2026.

³ ETS No. 123, Strasbourg, 1986) (European Convention for the Protection of Vertebrate Animals used for Experimental and Other Scientific Purposes. Retrieved from <https://rm.coe.int/168007a67b>. Accessed May 19, 2026.

Animals and Veterinary and Sanitary Examination of Meat and Meat Products”⁴.

The chemical composition of the meat was determined by the mass fraction of protein by the method based on the adsorption of the dye by proteins (calculation of total nitrogen according to Kjeldahl) and optical density data using a spectrophotometer PE 5300 VI (Russia) according to GOST 25011-2017⁵; moisture — drying the samples in the drying cabinet ShST GP 80–410 (Belarus) at a drying temperature of 100–105 °C according to GOST 33319-2015⁶; water-holding capacity (WHC) — planimetric pressing house according to Grau and Hamm in the Volovinskaya-Kelman modification⁷, based on moisture release (triplicate or more determinations) using electronic balance Pioneer (USA); fat was determined by the Soxhlet method, based on repeated extraction of fat with a solvent from a dried weighed amount of the product with further removal of the solvent and drying the fat to a constant mass on a Velp Scientifica SER 145 RS232 device (Italy) according to GOST 23042-2015⁸; ash determination was carried out using a method based on the determination of the mineral part of the products obtained after the combustion of organic substances in the Pro Mufel muffle furnace PM4-PTR (Russia) at $t = 500\text{--}700\text{ }^{\circ}\text{C}$ to constant weight according to GOST 31727-2012⁹; and pH — by potentiometric method using pH-meter Testo 205 (China) at a depth of 4–5 cm according to GOST R 57879-2017¹⁰.

Based on the obtained results, mean values for each indicator were calculated per animal group at the beginning of the experiment and at subsequent weighings. Mean values for average daily and absolute gains over the experimental period, as well as feed conversion ratios, were derived. The resulting experimental data were processed biometrically using one-way and two-way analysis of variance (ANOVA) in STATISTICA 13 RU software (“StatSoft, Inc.”, USA). Arithmetic means (M), standard error of the mean ($\pm m$), and significance levels (p) were calculated.

⁴ Rules for Veterinary Inspection of Slaughter Animals and Veterinary and Sanitary Examination of Meat and Meat Products. Approved by the General Directorate of Veterinary Ministry of Agriculture of the USSR December 27, 1983. Retrieved from <https://fsvps.gov.ru/files/veterinarno-sanitarnye-trebovaniya-p/> Accessed May 19, 2026 (In Russian)

⁵ GOST 25011-2017 «Meat and meat products. Protein determination methods». Moscow: Standartinform, 2018. Retrieved from <https://docs.cntd.ru/document/1200146783> Accessed May 19, 2026 (In Russian)

⁶ GOST 33319-2015 «Meat and meat products. Method for determination of moisture content». Moscow: Standartinform, 2019. Retrieved from <https://docs.cntd.ru/document/1200123927> Accessed May 19, 2026 (In Russian)

⁷ Volovinskaya, V. P., Kelman, B. Ya, (1962). Development of a method for determining the moisture absorption capacity of meat. Proceedings of All-Union Scientific Research Institute of the Meat Industry. Moscow: VNIIMP, 1962.

⁸ GOST 23042-2015 «Meat and meat products. Methods of fat determination». Moscow: Standartinform, 2019. Retrieved from <https://docs.cntd.ru/document/1200133107>. Accessed May 19, 2026 (In Russian)

⁹ GOST 31727-2012 (ISO 936:1998) «Meat and meat products. Determination of total ash content». Moscow: Standartinform, 2013. Retrieved from <https://docs.cntd.ru/document/1200098742>. Accessed May 19, 2026. (In Russian)

¹⁰ GOST R 57879-2017 «Agricultural pedigree cattle. Methods for determination of pigs productivity parameters». Moscow: Standartinform, 2013. Accessed May 19, 2026. (In Russian)

Results and discussion

The introduction of black soldier fly larvae meal (BSFLM) as a partial or complete substitute for fish meal (FM) in the diets of growing-fattening pigs had a differentiated effect on their growth performance, depending on the level of inclusion. At the beginning of the experiment, all groups had practically identical live weight ($\sim 28\text{ kg}$, $p = 0.99$) (Table 3). However, by the end of the grower period, the highest live weight was observed in group E3 (56.96 kg), exceeding the control group by 3.82 %. Group E2 also demonstrated good results (56.65 kg or 103.25 % of the control).

Numerous studies confirm that black soldier fly larva has significant value as a protein source for swine production. Insect meal has been used to feed piglets, and its influence on growth performance and pork quality has been studied. For instance, Maurer et al. [41] confirmed that an 8 % partial dietary replacement with black soldier fly did not negatively affect pig growth during the grower phase. Nevertheless, it should be noted that compared to the control group diets, no stimulating effect was observed in the experimental group, and average daily gain decreased by 7.2 %. Adding 4 % black soldier fly larvae meal significantly increased ADG and improved backfat thickness at the loin. Meat quality indicators when feeding insect meal at both 8 % and 4 % levels led to an increase in intramuscular fat content.

In our study, animals in all experimental groups exceeded the control group's ADG indicators ($p = 0.38$). The highest feed intake was recorded in group E2 (1926.3 g/head/day), which is 7.8 % higher than C. Group E3 consumed 2.4 % less compound feed than C. The best Feed Conversion Ratio (FCR) was achieved by group E3 (1.88 kg/kg gain), being 8.3 % more efficient than the control. Groups E1 and E2 also showed lower FCR compared to the control (by 3.5 % and 1.4 %, respectively, $p = 0.363$). Thus, replacing fish meal with black soldier fly larvae meal positively influenced pig productivity. Full replacement of FM with BSFLM (group E3) proved most effective, demonstrating the best FCR and high live weight (LW) gain at the lowest feed intake. Group E2 (partial replacement) showed the maximum ADG, but with higher compound feed consumption. Over the entire 97-days trial period, group E3 showed the maximum absolute gain (90.32 kg and 1038.16 g/day), exceeding the control figures by 5.37 %. All experimental groups E showed better feed conversion compared to group C. The most efficient conversion was noted in group E1 (2.71 kg/kg gain), which is 9.1 % better than the control. Groups E2 and E3 also demonstrated FCR improvements of 3.8 % and 2.8 %, respectively.

Similarly, in the study by Chia et al. [29], using diets with varying contents of black soldier fly larvae found no significant effect on mass indices and ADG in pigs. Meanwhile, body weight differed depending on diet ($p < 0.001$) and sex ($p = 0.005$). Body weight indices significantly increased from week 1 to week 9 regardless of sex ($p < 0.001$).

Table 3. Dynamics of live weight and feed conversion ratio by experimental periods ($n = 6$, $M \pm m$)

Indicator	Groups				<i>p</i> -value
	C	E1	E2	E3	
Growing phase – 30 days					
Initial live weight (at placement), kg	28.57 ± 1.24	28.17 ± 1.17	28.10 ± 0.60	28.17 ± 1.68	0.99
Final live weight, kg	54.87 ± 2.04	55.38 ± 1.27	56.65 ± 0.89	56.96 ± 2.49	0.80
% of control	100.00	100.94	103.25	103.82	—
Average daily gain (ADG), g	876.67 ± 40.54	907.22 ± 35.61	951.67 ± 26.95	944.00 ± 25.59	0.38
% of control	100.00	103.49	108.56	107.68	—
Feed intake, g/head/day	1787.5 ± 45.3	1786.5 ± 53.6	1926.3 ± 76.3	1744.3 ± 74.9	0.23
% of control	100.00	99.9	107.8	97.6	—
Feed conversion ratio (FCR), kg feed/kg gain	2.05 ± 0.08	1.98 ± 0.08	2.03 ± 0.07	1.88 ± 0.05 ^b	0.36
% of control	100.00	96.5	98.6	91.7	—
1st Fattening period — 31 days					
Final live weight, kg	87.42 ± 3.66	87.77 ± 2.73	91.37 ± 1.86	90.40 ± 3.67	0.74
% of control	100.00	100.40	104.52	103.41	—
Average daily gain (ADG), g	1085.00 ± 59.55	1079.44 ± 50.67	1157.22 ± 54.31	1114.67 ± 43.57	0.71
% of control	100.00	99.49	106.66	102.73	—
Feed intake, g/head/day	3024.9 ± 126.6	2895.3 ± 135.6	3260.4 ± 143.9	3201.7 ± 113.8	0.22
% of control	100.00	95.7	107.8	105.8	—
Feed conversion ratio (FCR), kg feed/kg gain	2.89 ± 0.05	2.79 ± 0.12	2.92 ± 0.09	2.97 ± 0.07	0.51
% of control	100	96.3	100.9	102.8	—
2nd Fattening period — 26 days					
Final live weight, kg	114.28 ± 4.72	113.78 ± 3.43	118.13 ± 3.33	118.96 ± 3.40	0.71
% of control	100.00	99.56	103.37	104.09	—
Average daily gain (ADG), g	995.06 ± 53.92	963.58 ± 32.91	991.36 ± 67.39	1057.78 ± 32.36	0.64
% of control	100.00	99.49	106.66	102.73	—
Feed intake, g/head/day	4140.1 ± 215.1	3372.4 ± 117.5 ^a	3827.2 ± 243.3	4184.8 ± 133.7	0.02
% of control	100.00	81.5	92.4	101.1	—
Feed conversion ratio (FCR), kg feed/kg gain	4.02 ± 0.09	3.39 ± 0.15 ^a	3.73 ± 0.12 ^b	3.81 ± 0.11	0.01
% of control	100.00	84.4	93.0	95.0	—
Entire experimental period					
Initial live weight (at placement), kg	28.57 ± 1.24	28.17 ± 1.17	28.10 ± 0.60	28.17 ± 1.68	0.99
Final live weight, kg	114.28 ± 4.72	113.78 ± 3.43	118.13 ± 3.33	118.96 ± 3.40	0.71
Absolute gain over the period, kg	85.72 ± 3.96	85.62 ± 3.21	90.03 ± 3.52	90.32 ± 1.50	0.61
Average daily gain (ADG), g	985.25 ± 45.49	984.10 ± 36.90	1034.87 ± 40.44	1038.16 ± 17.26	0.61
% of control	100.00	99.88	105.04	105.37	—
Total feed intake, kg/head	2931.5 ± 117.7	2655.5 ± 83.2 ^b	2969.8 ± 135.0	3011.8 ± 91.6	0.13
% of control	100.00	90.6	101.3	102.7	—
Feed conversion ratio (FCR), kg feed/kg gain	2.98 ± 0.06	2.71 ± 0.11 ^a	2.87 ± 0.08	2.90 ± 0.06	0.05
% of control	100.00	90.9	96.3	97.3	—

Significant vs. control: ^a — $p < 0.05$; tendency: ^b — $p < 0.10$. Compiled by the authors.

No significant interaction between diet and age ($p = 0.110$) or between sex and age regarding body weight ($p = 0.388$) was detected. Furthermore, interactions between diet, sex, and age on body weight were also non-significant ($p = 0.345$). Body weight gain over the entire experimental period was independent of diet ($p = 0.351$), sex ($p = 0.486$), and there was no correlation between diet and sex ($p = 0.340$). Inclusion of partially defatted insect-based rations (at 10 %) allows increasing daily feed intake for weaned piglets from day 24 to 61 due to enhanced palatability. Piglets in the weaning period were fed a diet containing 8 % black soldier fly larvae and 41 %, as well as a defatted ration containing 8 %, without revealing any impact on their growth performance.

Similarly to our research, Crosbie et al. [42] studied the effect of partial replacement of animal protein sources with black soldier fly larvae meal in weanling piglet diets from 21 days of age (initial weight 6.74 ± 0.23 kg) on growth performance. Partial replacement with low (25 %) and high (50 %) fat content was used. Pig ADG was 496 ± 13 g and final weight 27.61 ± 0.66 kg, with no differences between experimental groups. The authors suggested using diets with BSF protein substitution of at least 50 %, as such feeds do not lead to any negative consequences regarding pig growth indicators.

Further work is underway to refine other components of the black soldier fly larva. The aim of the study by van Heugten et al. [43] was to determine the possibility of

improving weanling piglet performance by replacing corn oil with black soldier fly larvae oil in the diet. An increase in ADG and improved feed efficiency was noted, leading to increased pig body weight after a 40-day trial. However, data regarding the maximum inclusion percentage of black soldier fly larvae meal remains insufficient. It was revealed that feeding black soldier fly larvae meal with 30 % and 50 % replacement in the diet was accompanied by reduced growth rates.

The research by Yordanova et al. [44] aimed to compare productive performance, nutritional value, and nutrient digestibility in pigs fed graded levels of *Hermetia illucens* L. larvae meal (0, 30, 60, 90, and 120 g/kg diet) instead of soybean meal at 38 days and from 119 to 157 days of age. Replacing soybean meal did not alter growth performance ($p > 0.05$) and energy values, as only a linear increase in dietary fat digestibility was observed ($p < 0.001$). This might have occurred due to the high fat content of the insect larva. Pig body weight at the start and end of the study was 31.86 kg and 59.66 kg, respectively. The absence of difference in growth performance at 120 g/kg (over 50 % of the diet) allows considering the use of insect meal in pig diets during the grower phase. Other researchers also found no significant difference in growth indicators when feeding 100 g/kg and 120 g/kg insects replacing soybean meal.

Previously obtained studies revealed that black soldier fly larvae feed can be used in the diet of weaned pigs at concentrations of 8 % and 18.5 % during pig rearing without any harmful effects on growth performance. According to the results obtained by Jin et al. [45], dietary supplements containing 8 % larvae fat improved overall growth indicators in a dose-dependent manner. Feeding piglets diets at concentrations below 4 % did not affect their growth indicators. Studies were also conducted on weaned piglets with 50 % dietary protein replaced by full-fat black soldier fly larvae meal calculated at ages 0–7 days (14.76 %), 7–21 days (7.5 %), and 21–42 days (1 %). This allowed identifying the diet's effect on body weight at 42 days and average daily gain over the entire 0–42 days period. Chia et al. [18] reported that increasing the larvae content in finishing pig diets from 9 % to 14 % instead of fish meal allowed increasing carcass yield, ADG, and FCR over the total rearing period, ultimately leading to increased carcass weight.

Based on the results of this study, as well as an analysis of available literature, it can be concluded that the inclusion of black soldier fly larvae meal (BSFLM) in pig diets is safe. In this context, the complete replacement of fish meal with BSFLM (Group E3–100 % substitution) proved to be the most effective strategy from both economic and digestive physiology standpoints. It ensured the best feed conversion ratio (8.3 % better than the control) and a high absolute live weight gain (+5.37 %) at the lowest compound feed intake. If the primary goal is achieving maximum growth rate (average daily gain), partial inclusion of the additive is optimal. In our experiment, Group E2 showed the highest ADG, which confirms literature

data. Inclusion levels ranging from 4 % to 14 % often act as growth stimulants without negatively affecting feed intake. Therefore, for intensive pig fattening, it is recommended to use a complete replacement of expensive fish meal with BSFLM (up to 100 %) to optimize costs and improve feed conversion. To achieve peak average daily gain indicators, an inclusion concentration of 8–14 % is effective. Black soldier fly larvae meal can be safely used as a full-fledged protein source, replacing traditional animal and plant components in the diet. However, one should consider the risk of growth retardation at very high inclusion levels (30–50 %), as reported in several other studies.

Boontiam et al. [46], adding 12 % insects to the diet, noted improved pig growth indicators (live weight gain increased by 18.7 %) and increased antioxidant capacity (SOD activity increased by 25.6 %). While replacing the diet with 3.5 % larvae product in piglets did not affect ADG, feed intake, or feed digestibility.

Data regarding the influence of black soldier fly products on meat productivity and meat quality also remain contradictory. It has been established that feeding black soldier fly (*Hermetia illucens*) larvae to pigs as an alternative protein and fat source exerts a complex positive effect on meat productivity and pork quality. One of the significant positive changes when using insects in the diet is the increase in intramuscular fat (marbling). High intramuscular fat directly affects tenderness, juiciness, and flavor. Moisture loss during storage in pigs receiving larvae feed additives is significantly reduced, indicating improved water-holding capacity.

Active acidity (pH) and meat color parameters (lightness, redness, yellowness) usually remain within physiological norms, meaning they do not fall into undesirable categories such as PSE (watery, pale, soft) or DFD (dark, firm, dry). Optimal inclusion of larvae (4–8 %) in pig diets improves average daily gain, reduces feed costs per unit of gain, and increases the ribeye area.

In pig farming, slaughter weight is a variable affecting production costs and product quality. During slaughter, residual glycogen content in tissues and postmortem glycolysis determine the rate of pH decline and ultimate pH, which in turn determines meat value. Carcass weight over 90 kg favorably affects the cooling rate and meat pH at 45 minutes and 24 hours post-slaughter, leading to increased water-holding capacity and decreased cooking losses. Slaughter indicators of animals depending on the studied group are presented in Table 4.

Table 4 provides a comparative analysis of the animals' slaughter indicators. The live weight after fasting was slightly higher in the experimental groups E2 (114.00 ± 2.95 kg) and E3 (115.06 ± 3.35 kg) compared to group E1 (110.13 ± 3.27 kg) and the control group (110.02 ± 4.78 kg), although these differences were not statistically significant ($p = 0.70$). The hot carcass weight reached its maximum in group E3 (85.49 ± 2.54 kg), while the lowest values were recorded in group E1 (80.19 ± 2.05 kg) and the control group (80.34 ± 4.21 kg); however, these variations were also minor

Table 4. Slaughter indicators (group mean, $M \pm m$, $n = 6$)

Indicator	Groups				<i>p</i> -value
	E1	E2	E3	C	
Live weight after fasting, kg	110.13 $\pm$ 3.27	114.00 $\pm$ 2.95	115.06 $\pm$ 3.35	110.02 $\pm$ 4.78	0.70
Carcass length, cm	108.17 $\pm$ 2.24	115.33 $\pm$ 1.56	110.40 $\pm$ 3.36	112.67 $\pm$ 3.05	0.26
Hot carcass weight, kg	80.19 $\pm$ 2.05	83.25 $\pm$ 2.09	85.49 $\pm$ 2.54	80.34 $\pm$ 4.21	0.55
Dressing percentage, %	72.86 $\pm$ 0.36	73.04 $\pm$ 0.34	74.30 $\pm$ 0.23	72.89 $\pm$ 0.69	0.14
Head weight, kg	7.73 $\pm$ 0.57	8.09 $\pm$ 0.17	7.94 $\pm$ 0.47	7.98 $\pm$ 0.24	0.92
Leg weight, kg	1.61 $\pm$ 0.09	1.71 $\pm$ 0.09	1.65 $\pm$ 0.07	1.68 $\pm$ 0.04	0.80
Liver weight, kg	1.59 $\pm$ 0.08	1.78 $\pm$ 0.05	1.76 $\pm$ 0.05	1.78 $\pm$ 0.06	0.11
Kidney weight, kg	0.38 $\pm$ 0.04	0.45 $\pm$ 0.02	0.40 $\pm$ 0.02	0.38 $\pm$ 0.02	0.23
Heart weight, kg	0.38 $\pm$ 0.02 ^b	0.47 $\pm$ 0.03	0.41 $\pm$ 0.02	0.48 $\pm$ 0.05	0.17
Spleen weight, kg	0.19 $\pm$ 0.02	0.17 $\pm$ 0.02	0.18 $\pm$ 0.01	0.18 $\pm$ 0.01	0.64
Lung weight, kg	0.84 $\pm$ 0.14	0.98 $\pm$ 0.02	0.90 $\pm$ 0.17	1.03 $\pm$ 0.06	0.60
Giblet weight, kg	12.73 $\pm$ 0.83	13.65 $\pm$ 0.22	13.24 $\pm$ 0.42	13.53 $\pm$ 0.30	0.58
Giblet yield, % of hot carcass	15.80 $\pm$ 0.68	16.43 $\pm$ 0.35	15.49 $\pm$ 0.19	17.01 $\pm$ 0.77	0.28
Backfat thickness between 6th and 7th thoracic vertebrae, mm	20.83 $\pm$ 2.01	26.67 $\pm$ 5.11	25.40 $\pm$ 2.68	26.33 $\pm$ 2.85	0.60
Backfat thickness at the loin, mm	18.33 $\pm$ 1.67	23.33 $\pm$ 4.01	18.00 $\pm$ 1.22	20.83 $\pm$ 2.94	0.52

Significant vs. control: tendency: ^b — $p < 0.10$. Compiled by the authors.

($p = 0.55$). The dressing percentage demonstrated a tendency to increase in the experimental groups, particularly in E3 (ranging from 72.86 $\pm$ 0.36 % in E1 to 74.30 $\pm$ 0.23 % in E3). Nevertheless, this trend did not reach statistical significance ($p = 0.14$).

The assessment of backfat thickness revealed no statistically significant differences between the groups. Measurements taken between the 6th and 7th thoracic vertebrae showed the lowest values in group E1 (20.83 $\pm$ 2.01 mm), although the difference compared to the control was not significant ($p = 0.60$). A similar trend was observed when evaluating loin fat depth, where the minimum indicators were also recorded in groups E1 and E3.

Morphological indicators of carcasses and qualitative characteristics of the meat are presented in Table 5.

An analysis of active acidity demonstrated the influence of experimental diets on glycolytic processes in muscle tissue. At 45 minutes post-slaughter, the pH value was significantly higher in the experimental groups compared to the control (6.00 $\pm$ 0.09), reaching its maximum in group E3 (6.32 $\pm$ 0.08; $p < 0.05$) and E2 (6.41 $\pm$ 0.18; $p < 0.10$). However, by 24 hours post-mortem, the pH value in group E2 decreased to 5.42 $\pm$ 0.05, which was significantly lower than the control figure (5.58 $\pm$ 0.05; $p < 0.05$). Despite the

lack of statistical significance ($p = 0.40$), a positive trend in the water-holding capacity (WHC) of muscle tissue was noted: in the experimental groups, this indicator ranged from 75.94 % to 76.63 %, exceeding the control value (73.04 %). The ribeye area (longissimus dorsi cross-sectional area), characterizing muscle development, reached its highest value in group E2 (80.51 $\pm$ 5.98 cm²). This exceeds the corresponding indicator of the control group (71.44 $\pm$ 3.74 cm²) by 12.7 %, although due to high data variability, the intergroup differences for this trait remained at the level of a tendency ($p = 0.14$).

Table 5 presents the chemical composition of pork across the control (C) and experimental groups (E1, E2, E3). The highest moisture content was recorded in the control group at 72.09 $\pm$ 0.16 %, which was statistically significantly higher than that in group E3 ($p < 0.05$). In the experimental groups, values were slightly lower: 71.24 $\pm$ 0.37 % for E1, 70.45 $\pm$ 1.00 % for E2, and 71.03 $\pm$ 0.20 % for E3. Overall differences between the groups did not reach statistical significance ($p = 0.17$). Group E3 demonstrated the highest protein level at 23.42 $\pm$ 0.09 %. This value was statistically significantly higher compared to group E2 ($p < 0.05$). Group E1 showed a tendency toward lower protein levels relative to the control (22.99 $\pm$ 0.19 %, $p < 0.10$), while group

Table 5. Qualitative parameters and chemical composition of pork (group mean, $M \pm m$, $n = 6$)

Indicator	Groups				<i>p</i> -value
	E1	E2	E3	C	
pH at 45 min, units	6.19 $\pm$ 0.13	6.41 $\pm$ 0.18 ^b	6.32 $\pm$ 0.08 ^a	6.00 $\pm$ 0.09	0.16
pH at 24 h, units	5.47 $\pm$ 0.06	5.42 $\pm$ 0.05 ^a	5.52 $\pm$ 0.03	5.58 $\pm$ 0.05	0.12
Water-Holding Capacity (WHC), %	75.94 $\pm$ 1.54	75.11 $\pm$ 1.47	76.63 $\pm$ 1.85	73.04 $\pm$ 1.30	0.40
Ribeye area, cm ²	65.58 $\pm$ 3.36	80.51 $\pm$ 5.98	73.59 $\pm$ 3.76	71.44 $\pm$ 3.74	0.14
Moisture, %	72.09 $\pm$ 0.16 ^a	71.24 $\pm$ 0.37	70.45 $\pm$ 1.00	71.03 $\pm$ 0.20	0.17
Protein, %	23.36 $\pm$ 0.08	22.99 $\pm$ 0.19 ^b	22.85 $\pm$ 0.21 ^a	23.42 $\pm$ 0.09	0.03
Fat, %	3.44 $\pm$ 0.20 ^a	4.69 $\pm$ 0.45	5.58 $\pm$ 1.17	4.50 $\pm$ 0.17	0.11
Ash, %	1.11 $\pm$ 0.04	1.08 $\pm$ 0.03	1.12 $\pm$ 0.07	1.05 $\pm$ 0.02	0.66

Significant vs. control: ^a — $p < 0.05$; tendency: ^b — $p < 0.10$. Compiled by the authors.

E2 had the lowest mean value at $22.85 \pm 0.21\%$. The overall intergroup difference was significant ($p = 0.03$). The control group exhibited the lowest fat percentage at $3.44 \pm 0.20\%$, being significantly different from group E2 ($p < 0.05$). Fat accumulation increased notably in the experimental diets. Thus, E1 contained $4.69 \pm 0.45\%$, E2 peaked at $5.58 \pm 1.17\%$, and E3 reached $4.50 \pm 0.17\%$. However, these variations among the treatments were not statistically significant ($p = 0.11$). Mineral content (ash) remained relatively stable across all samples with no statistically significant differences observed ($p = 0.66$). Values ranged narrowly from $1.05 \pm 0.02\%$ in group E3 to $1.12 \pm 0.07\%$ in group E2. The control group measured $1.11 \pm 0.04\%$, and group E1 measured $1.08 \pm 0.03\%$.

Similarly, other authors have demonstrated that using products from defatted *Hermetia illucens* larvae in pig diets allows for obtaining a meat product comparable to that produced using soy, with little difference in many indicators such as odor and juiciness. Yu et al. [39] tested two diets containing 4% and 8% black soldier fly larvae meal for fattening pigs and reported increased meat marbling, whereas no effect on pH, color, water-holding capacity, or tenderness was noted. It is possible that the use of black soldier fly larvae meal improves meat quality in pigs through dietary modulation of lipid metabolism and antioxidant function.

Consistent with our data, Chia et al. [18], when feeding high levels of insects (up to 100%), found that their inclusion at various levels was acceptable and well-tolerated by pigs. They studied feed intake, body weight gain, and feed conversion ratio over a 98-day experiment without observing a significant decline in animal growth performance. Diet significantly influenced pig growth traits; specifically, the carcass weight of pigs fed diets replacing soybean meal with black soldier fly larvae at 50%, 75%, or 100% was higher than that of pigs receiving the control diet (100% soybean meal as the protein source). Crude protein content in pork was high (65–93% on a dry matter basis) across all studied groups. This indicates that insects can be used as a protein source for pig fattening. When feeding insects with higher substitution levels in feeds (50–100%), an increase in body weight, improved feed conversion, and higher carcass yields were identified compared to animals fed the control diet. Backfat thickness at the loin increased depending on the fed diet and differed significantly at 100% replacement ($P = 0.004$) from groups using 25%, 50%, and the control. While in barrows and gilts this indicator was significantly lower at 100% replacement compared to control animals. The backfat thickness values in the studied animals did not differ statistically. Spleen weight was significantly greater in pigs fed diets with higher insect larvae content compared to low content, whereas heart, liver, kidney, and lung weights did not differ significantly between groups.

Meat quality is the most important factor for the consumer. Physical qualities of meat, such as moisture, ribeye area, pH45 and pH24, as well as intramuscular fat content,

are most often used to assess its quality. Muscle fiber composition is closely related to physical meat properties and affects juiciness, tenderness, and flavor. A positive correlation of these indicators with intramuscular fat is noted. In the studies of Zhu et al. [40], when adding black soldier fly larvae meal to the diet of growing pigs, meat indicators were studied. An increase in intramuscular fat content is beneficial for improving meat quality. According to results obtained by Zhu et al. [40], feeding black soldier fly larvae meal led to an increase in subcutaneous fat cell volume, an increase in backfat thickness at the loin, and a decrease in ribeye area. Meat quality improved due to increased intramuscular fat content, as in growing pigs it increases due to feeding. From the point of view of water-holding capacity, this indicator was much lower than in control animals. On the other hand, adding black soldier fly larvae to animal diets did not affect meat pH at 45 minutes and 24 hours post-slaughter, nor meat color, marbling degree, or cooking losses.

The results obtained in the present study regarding carcass traits indicate that replacing fish meal with black soldier fly larvae meal (BSFLM) did not have a negative impact on pork productivity. Although there were no statistically significant differences in hot carcass weight or dressing percentage between the groups, a positive trend was observed. Animals from group E3 (100% replacement) demonstrated the highest absolute live weight gain (+5.37% compared to control) and the most efficient feed conversion ratio (−8.3% compared to control). These findings are consistent with previous reports by Chia et al. [18] and Yu et al. [39], who also noted an increase in carcass yield when using high levels of insect meal as a substitute for soybean meal. Regarding meat quality parameters, our data revealed certain physiological shifts. The pH45 values tended to be higher in experimental groups (up to 6.41 ± 0.18 in E2), which may indicate a slower rate of postmortem glycolysis. Furthermore, water-holding capacity (WHC) showed a slight improvement in the experimental diets (up to 76.63% in E3) compared to the control (73.04%), although these differences did not reach statistical significance ($p = 0.40$). This aligns with literature data suggesting that BSFLM inclusion does not deteriorate technological properties such as color, tenderness, or cooking losses. In terms of chemical composition, the protein content was significantly higher in group E1 ($72.09 \pm 0.16\%$, $p < 0.05$ vs. control), confirming the high biological value of insect-derived amino acids. Conversely, intramuscular fat content decreased in groups E2 and E3 ($p < 0.05$ – 0.10), indicating a modulation of lipid metabolism at higher substitution levels. While some studies report increased backfat thickness or marbling when feeding insects, our results suggest that complete replacement of marine proteins promotes leaner muscle growth without compromising overall tissue development. Thus, *Hermetia illucens* larvae can be considered a sustainable alternative source of protein that ensures stable slaughter performance and yields high-quality pork suitable for modern intensive farming systems.

Conclusions

The obtained results allow us to consider black soldier fly larvae meal not merely as a cost-effective protein source, but as a functional feed additive. Its efficacy stems from a combination of factors: a balanced amino acid spectrum, chitin acting as a prebiotic substrate for gut microbiota, and specific bioactive compounds. The absence of decline in productivity even with 100 % replacement of fish meal addresses two critical industry challenges simultaneously: ensuring food security amidst rising prices for traditional

marine-based ingredients and solving the environmental problem of organic waste recycling, as BSF larvae effectively convert various substrates into biomass. It should be noted that economic efficiency will depend heavily on the scale of industrial production of BSFLM. Nevertheless, considering the improvements in feed conversion and potential premiums for “eco-friendly” or “functional” meat enriched with natural bio supplements, the use of this ingredient appears promising for modern intensive pig farming systems.

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