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REVIEWS IN Aquaculture

REVIEW

A systematic meta-analysis based review on black soldier fly (*Hermetia illucens*) as a novel protein source for salmonids

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Abstract

Black soldier fly (*Hermetia illucens*) has gained attention as a sustainable novel protein source in fish feed due to its high nutritional value and low environmental impacts. In the past decade, effects of the use of black soldier fly in aquafeeds have widely been studied in salmonids. A meta-analysis was conducted to compile and systematically quantify the effect of black soldier fly in diets for salmonids on growth performance and nutrient utilization. The main meta-analysis showed that dietary inclusion of black soldier fly did not compromise the specific growth rate, feed conversion ratio, feed intake, protein digestibility and protein efficiency ratio in salmonids. A meta-regression was conducted to explore the possible causes of variation in growth rate, feed conversion ratio and feed intake between the studies. Fish species, protein source(s) replaced and black soldier fly inclusion level were partially responsible for the variation in growth rate between the studies. The protein source(s) replaced and black soldier fly inclusion level partially explained the variation in feed conversion ratio and feed intake respectively. The sub-data sets sorted according to the replaced protein source(s) showed that replacing fishmeal by black soldier fly decreased growth rate and feed intake in salmonids, but replacing non-fishmeal sources improved growth rate and feed conversion. This strengthened the importance of the type of replaced protein source(s) when evaluating nutritional values of black soldier fly for salmonids. In conclusion, the present meta-analysis showed that black soldier fly is a promising protein source for salmonid feeds.

KEYWORDS
fishmeal replacement, insect meal, meta-analysis, meta-regression, nutrient utilization, salmonids

1 | INTRODUCTION

Insect meals have received an increasing attention in recent years as a sustainable protein source for aquafeeds,[1] because insects are able to utilize organic side streams, and the production does not require any agricultural land, has low water usage and contributes to lower greenhouse gas emissions.[2] The approval of use of processed insects in aquafeeds by the European Commission (Regulation 2017/893/EC, 2017) further promotes upscaling of insects as a novel protein source. One of the most favourable insect species to be used in feed is black soldier fly (*Hermetia illucens* Linnaeus, 1758) (BSF).[3] BSF is a good source of protein, lipid and minerals.[4] Furthermore, BSF is capable of converting low-quality organic material efficiently into high-quality nutrients,[5] although the possibility of using low-quality organic material as a substrate for growing insects is still limited by the regulatory framework in Europe. BSF is a good candidate for large-scale production due to its high growth rate and feed conversion efficiency, potential to be reared on organic side streams and suitability for automation.[3] In addition to nutritive value, BSF also contains bioactive compounds such as chitin, lauric acid and antimicrobial peptides, which can have health beneficial effects in animals.[6]

With the identification of great potential of BSF as a sustainable novel protein source in fish feed, the effects of the use of BSF in diets for salmonids such as Atlantic salmon (*Salmo salar*) and rainbow trout (*Oncorhynchus mykiss*) have widely been studied, focusing on growth performance, nutrient utilization, gut microbiota,[7,8] gut health and immune responses.[9,10] In literature, the studies on growth performance and nutrient utilization reported high variation in success of fish responses to BSF in diets. The use of BSF in diets was shown to have no effects,[11–14] negative effects[11,12,14] or even positive effects[15] on growth performance and nutrient utilization in salmonids. Furthermore, previous studies showed dose-dependent responses in fish to increasing dietary BSF levels or protein replacement levels.[11,14] In a recent review, English et al.[16] also discussed the inconsistency of results obtained in different studies investigating the effects of the use of BSF in diets on salmonid growth performance and nutrient utilization. The diverse nature of BSF rearing, downstream processing and study designs makes it difficult to directly compare the reported results to draw a general conclusion and to determine the dose-dependent responses across the studies.

Meta-analysis is a method to compile and statistically analyse results from a number of individual studies addressing similar research questions and produce integrated and broader interpretations. Recently, this approach was used to examine the effect of replacing fishmeal with insect meals on specific growth rate (SGR) of fish[17] and to determine the nutritional value of insects in aquafeeds.[18] These meta-analyses included data for various insect species as well as various aquatic species. The results of these two studies further emphasized that the analysis of individual insect and aquatic species can be more meaningful than the generalized results across different insect and aquatic species. The previous reviews on the topic of the effects of the use of BSF in salmonid diets concentrated on summarizing scientific literature in a narrative and qualitative approach.[16,19] The effect of BSF in salmonid diets has not yet been evaluated using a quantitative meta-analysis based approach according to our knowledge. In addition, the reasons of the inconsistency in success associated with the use of BSF in diets are important to identify in order to optimize the use of BSF in salmonid diets and design experiments. According to our knowledge, none of the previous meta-analyses took into consideration factors such as fish species, feed processing techniques, type of protein source(s) replaced by insects and developmental stage of insects that can influence the fish response to dietary insects. Therefore, in the present study, a meta-analysis was conducted to 1) systematically review and summarize data from previous studies to determine the effect of dietary BSF on SGR, feed conversion ratio (FCR), feed intake, apparent digestibility coefficient (ADC) of protein and protein efficiency ratio (PER) in salmonids and 2) identify the factors causing the variation in response of salmonids to the use of BSF in diet.

2 | MATERIALS AND METHODS

2.1 | Literature search and data set

The present meta-analysis was conducted adhering to the principles in the Cochrane Handbook for Systematic Reviews of Interventions[20] and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement.[21] A systematic literature search was conducted in ISI WEB OF KNOWLEDGE (1945–2021) and SCOPUS (1939–2021) on 11–15 March 2021, using the following search terms in combination with Boolean operators: insect; insects; black soldier fly; *H. illucens*; salmon; Atlantic salmon; *S. salar*; Coho salmon; *Oncorhynchus kisutch*; Chinook salmon; *Oncorhynchus tshawytscha*; trout; rainbow trout and *O. mykiss*. The terms were used to search Topic in ISI WEB OF KNOWLEDGE and Title-Abstract-Keywords in SCOPUS. The literature search strategy was supplemented with manual searches.

The selection process of studies to be included in the meta-analysis data set is shown in Figure 1. To prevent selection bias, following prespecified inclusion criteria were used: 1) The presence of a control group that did not include BSF; 2) protein source(s) in the control diet replaced by BSF; 3) studies investigated the effects of BSF on the growth performance (SGR, FCR and/or feed intake) or nutrient utilization (ADC of protein and PER) in salmonids. A study was considered as a growth study if the fish were fed for minimum 7 weeks or the fish at least doubled in weight during the feeding period; 4) reported standard deviation or standard error mean and 5) written in English. In addition, the data set included studies with nutrient balanced (major nutrients and/or amino acids) experimental diets to avoid the nutrient imbalances interference with the results. Duplicate reports, reviews and conference proceedings were not included. If a study contained more than one control diet, relevant BSF diets were compared separately with each individual control. When a study contained more than two treatments providing more than one comparison to the meta-analysis, the comparisons were individually coded.

Relevant data were extracted from each study using a standardized pro forma. Data extracted included: growth performance and/or nutrient utilization parameters including SGR, FCR, feed intake, ADC of protein and PER (calculated based on Equations (1), (2), (3) and (4)), number of experimental units per treatment, salmonid species, life stage of salmon, final body weight of fish, feed production method, type of protein source(s) replaced by BSF, developmental stage of BSF, processing method of BSF, dietary inclusion level of BSF, dietary chitin level and fishmeal replacement level. The fishmeal replacement level of BSF diets was calculated as [(Fish meal in

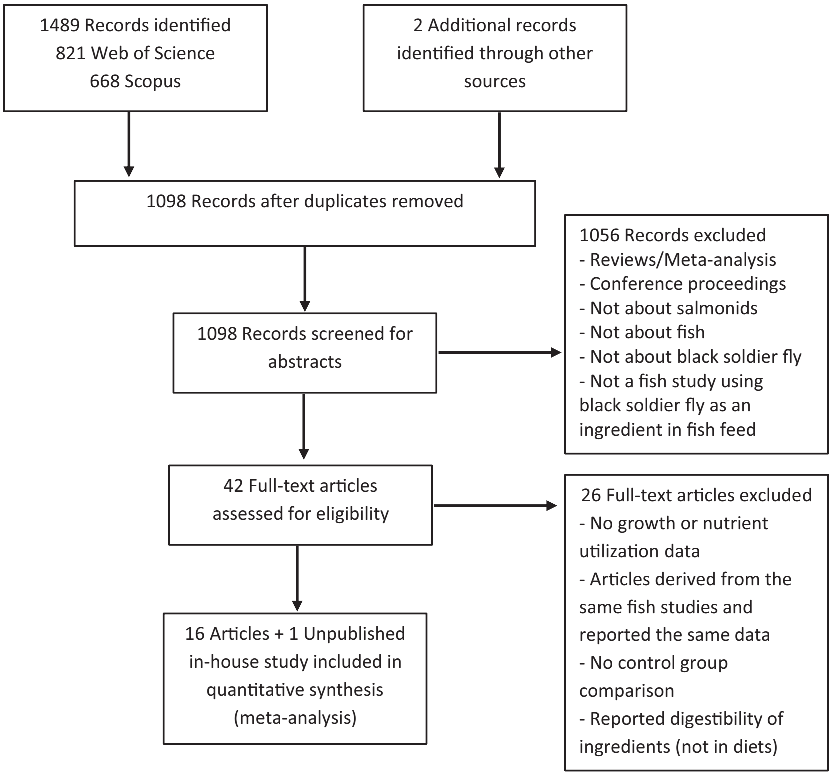


FIGURE 1 Selection of studies to be included in the meta-analysis data set. The selected 16 studies[11–15,28,31,37,43,54,71,81,94–97]

the control diet (%) − Fishmeal in the BSF diet (%))/Fishmeal in the control diet (%)] × 100. In addition, the standard deviation or standardized error mean of SGR, FCR, feed intake, ADC of protein or PER from control and BSF diets-fed groups were extracted. Feed intake values were reported in numerous ways in the studies. Therefore, the feed intake values per fish per day were calculated using available information in reported studies, and the standard deviations of calculated feed intake values were determined using the prognostic method described by Ma et al.[22]

$$\mathrm{SGR} = \frac{\ln \mathrm{FBW} - \ln \mathrm{IBW}}{t} \times 100, \tag{1}$$

where FBW = final body weight, IBW = initial body weight, t = number of days.

$$\mathrm{FCR} = \frac{\mathrm{FI}}{\mathrm{BWG}} \tag{2}$$

where FI = feed intake, BWG = body weight gain.

$$\text{ADC of protein} = \left(1 - \frac{M_D}{M_F} \times \frac{P_F}{P_D}\right) \times 100 \tag{3}$$

where M_D = marker concentration in diet, M_F = marker concentration in faeces, P_F = protein concentration in faeces, P_D = protein concentration in diet.

$$\mathrm{PER} = \frac{\mathrm{BWG}}{\mathrm{PI}} \tag{4}$$

where BWG = body weight gain, PI = protein intake.

2.2 | Statistical analysis

The differences in growth performance and nutrient utilization parameters between control diets and BSF diets-fed fish within studies were calculated using a standardized effect size; Hedges' g (calculated based on Equations (5), (6) and (7)). The Hedges' g corrects for bias with small sample sizes and produces a statistical standardization of the findings for each study.[23]

The Hedges' g was calculated as:

$$\frac{\overline{X}_B - \overline{X}_C}{S_p} J \tag{5}$$

where $\overline{X}$ is the mean for the BSF (B) and control (C) groups, S_p is the pooled sample standard deviation and J is a correction factor for bias with small sample sizes.

The pooled standard deviation (S_p) was calculated as:

$$S_P = \sqrt{\frac{(n_B - 1)\,\mathrm{SD}_B^2 + (n_C - 1)\,\mathrm{SD}_C^2}{n_B + n_C - 2}} \tag{6}$$

The correction factor (J) was calculated as:

$$J = 1 - \frac{3}{4\,(n_B + n_C - 2) - 1} \tag{7}$$

where n is the sample size and SD is the standard deviation of the BSF (B) and control (C) groups.

The meta-analysis was performed in comprehensive meta-analysis version 3 software (Biostat Inc.) using random effects models to account for the variation among the populations of studies. The presence of true heterogeneity between the studies was identified with Cochran's Q-test[24] and the proportion of observed heterogeneity caused by true effects was quantified using I^2 statistics.[25] When significant heterogeneity was detected, meta-regression analysis was conducted to explore the possible causes of heterogeneity. The categorical variables including fish species (Atlantic salmon vs. rainbow trout), feed production method (extrusion vs. pelleting), type of protein source(s) replaced (fishmeal vs. fishmeal +plant protein sources vs. non-fishmeal), BSF development stage (larvae vs. prepupae/pupae) and BSF processing method (full fat vs. defatted) and two continuous variables including dietary inclusion level of BSF and fish body size were included in the meta-regression analysis. Further differentiations of other variables were not possible due to the limited number or lack of data for carrying out a meaningful analysis. Meta-regression was not conducted with ADC of protein and PER data due to lack of data points in at least one group of each categorical variable. In addition, meta-analysis was conducted in sub-data sets sorted from the full data set according to the fish species, life stage of salmon, type of protein source(s) replaced, BSF development stage, BSF processing method and feed production method. Estimated effect sizes were visually displayed in forest plots created with comprehensive meta-analysis version 3 software (Biostat).

Linear and quadratic regression analyses between dietary inclusion level of BSF, dietary chitin level or fishmeal replacement level and effect sizes of SGR, FCR, feed intake, ADC of protein or PER were performed using IBM SPSS Statistics 27 software (IBM Corp.). The graphs were created using GraphPad Prism 9.0.0 software (GraphPad Software).

The chosen level of significance was $p < 0.05$ and threshold level of tendency was $p < 0.1$. The possible publication bias was not conducted in the present study due to the occurrence of substantial heterogeneity with all outcomes, which may lead to false-positive claims for publication bias.[26]

3 | RESULTS

The nutritional compositions of BSF larvae, prepupae and pupae are shown in Table 1. The BSF on average contains 36–39% protein and 28–34% lipid. The amino acid profiles of BSF differ from mealworm (*Tenebrio molitor*) and house fly (*Musca domestica*) (Table S1). The BSF contains lower content of most of the essential amino acids than fishmeal, especially lysine (5.6–6.4% of protein) and methionine (1.7% of protein) (7.8 and 3% of protein, respectively, in fishmeal) (Table S2). The methionine content in BSF is superior to that in soy protein (1.4% of protein) (Table S2). The essential amino acid profile shows that BSF in general meets the amino acid requirements of Atlantic salmon and rainbow trout[27] (Table S2), except for lysine and methionine. However, the values in NRC[27] are more than a decade old and advances in genetic and breeding programmes over the years have changed the nutritional requirements of salmonids.

The meta-analysis data set consisted of 16 publications in peer-reviewed journals and one unpublished in-house study (Table S3). Amongst these studies, 13 studies reported the nutritional composition of used BSF ingredients (Table S4). The studies were reported between 2007 and 2021. Either BSF larvae, prepupae or pupae were used in these studies in full-fat or defatted form. The BSF was included in the experimental diets by replacing traditional protein sources such as fishmeal, plant protein sources and/or animal protein sources, and the BSF inclusion levels in diets ranged from 5% to 60%. The sample sizes of studies ranged from two to four experimental units/treatments.

Amongst the selected studies, 13 studies were used to conduct the meta-analysis for SGR (36 comparisons) and all the 17 studies were used for FCR (49 comparisons) and feed intake (50 comparisons). The most studied salmonid species was rainbow trout (i.e. 11 studies) accounting for 50%, 53% and 54% of the SGR, FCR and feed intake data, respectively, whereas Atlantic salmon accounted for 50%, 47% and 46% of the SGR, FCR and feed intake data respectively. Amongst Atlantic salmon, four studies used pre-smolts and two studies used post-smolts. Seven studies (19 comparisons) were used to conduct the meta-analysis for ADC of protein. Atlantic salmon accounted for 68% of the ADC of protein data, whereas rainbow trout accounted for 32% of the data. Although two additional studies reported ADC of protein, one study was excluded from the analysis being an outlier as it gave extreme effect sizes,[28] and the other one was excluded because ADC of protein was reported as a graphical presentation.[13] Eight studies (21 comparisons) were used to conduct the meta-analysis for PER. Atlantic salmon accounted for 71% of the PER data, whereas rainbow trout accounted for 29% of the data.

3.1 | Specific growth rate

The forest plot in Figure 2 shows the pooled effect of the use of BSF in diets on SGR in salmonids. In the full data set of SGR, the Hedges' g between BSF diets and control diets ranged from −5.71 to 8, with 78% of the comparisons showing an increase or no change in SGR in fish fed BSF diets compared to control diets. The meta-analysis of SGR showed a mean effect size of −0.014 (Confidence interval: −0.615 to 0.586). On average, SGR in salmonids fed BSF diets did not differ from those fed the control diets. The test of heterogeneity, Q-value was 168.0 with a corresponding p value of <0.001, showing a significant heterogeneity in true effect sizes of SGR between the studies. Furthermore, the I^2 statistic showed that 79.2% of the observed heterogeneity was caused by the true effects rather than the sampling error. The variance of true effects (T^2) was 2.5 and the standard deviation of true effects (T) was 1.6.

According to the meta-regression, fish species, protein source(s) replaced and dietary BSF level partially caused the heterogeneity

TABLE 1 Proximate (% dry matter), mineral (g kg^{-1} dry matter), amino acid (% of crude protein) and fatty acid (% of total fatty acids) compositions of different developmental stages of black soldier fly (BSF)

	Larvae		Prepupae		Pupae	
Nutrient	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Dry matter (%)	32	5.3 (27)	35	5.9 (11)	40 (1)	
Crude protein	39	6.1 (58)	37	6.0 (16)	36	6.7 (2)
Crude lipid	28	8.7 (14)	34	9.2 (11)	28	17 (2)
Chitin	4.8	1.5 (9)	7.2	1.8 (9)	6.3 (1)	
Ash	10	4.5 (29)	10	4.6 (10)	14	7.4 (2)
Minerals						
Calcium	22	7.8 (12)	34	24 (5)	44 (1)	
Phosphorous	8.4	1.7 (17)	4.7	0.8 (5)	6.3 (1)	
Potassium	17	4.2 (12)	5.8	0.9 (5)	6.1 (1)	
Sodium	5	3.9 (12)	0.9	0.4 (5)	1.7 (1)	
Magnesium	3.8	1.3 (12)	2.8	0.6 (5)	3.7 (1)	
Manganese	0.2	0.05 (12)	0.2	0.1 (5)	0.4 (1)	
Iron	0.3	0.07 (12)	0.2	0.2 (5)	0.07 (1)	
Iodine	0.1	0.08 (10)				
Zinc	0.1	0.03 (11)	0.09	0.05 (4)	0.07 (1)	
Essential amino acids						
Arginine	4.8	0.6 (40)	4.8	1.1 (9)	5.5 (1)	
Histidine	2.7	0.5 (40)	3.0	0.7 (10)	3.4 (1)	
Isoleucine	4.2	0.7 (40)	4.2	0.9 (10)	4.7 (1)	
Leucine	6.6	0.8 (40)	6.6	1.4 (10)	7.8 (1)	
Lysine	5.9	1.0 (40)	5.6	1.3 (10)	6.4 (1)	
Methionine	1.7	0.3 (40)	1.7	0.4 (10)	1.7 (1)	
Phenylalanine	3.9	0.8 (40)	3.8	0.9 (10)	4.1 (1)	
Threonine	3.8	0.4 (40)	3.8	0.9 (10)	4.3 (1)	
Tryptophan	1.8	0.9 (21)	1.4	0.3 (6)	1.6 (1)	
Valine	5.8	0.7 (40)	5.8	1.3 (10)	6.8 (1)	
Non-essential amino acids						
Alanine	6.4	0.9 (35)	6.0	1.5 (8)	6.8 (1)	
Aspartic acid	8.6	0.9 (35)	8.3	2.2 (8)	11 (1)	
Glycine	5.1	0.6 (35)	5.1	1.3 (8)	6.5 (1)	
Glutamic acid	11	1.4 (34)	9.9	2.5 (8)	11 (1)	
Cysteine	0.8	0.7 (23)	1.1	1.0 (8)	0.8 (1)	
Tyrosine	5.7	1.4 (36)	5.9	2.0 (5)	6.8 (1)	
Proline	5.6	1.0 (34)	5.2	1.3 (8)	6.2 (1)	
Serine	4.2	0.4 (34)	4.1	1.5 (8)	4.7 (1)	
Fatty acids						
C12:0	37	9.9 (58)	43	11.9 (27)	65 (1)	
C14:0	7.5	1.4 (58)	6.9	2.0 (27)	9.7 (1)	
C16:0	16	3.1 (58)	13	3.6 (27)	8.6 (1)	
C16:1n7 (C16:1)	3.5	2.2 (55)	5.9	3.8 (27)	2.8 (1)	
C18:0	2.9	0.9 (58)	1.8	0.8 (27)	1.2 (1)	
18:1n9	13	4.3 (58)	12	5.0 (23)	6.8 (1)	

(Continues)

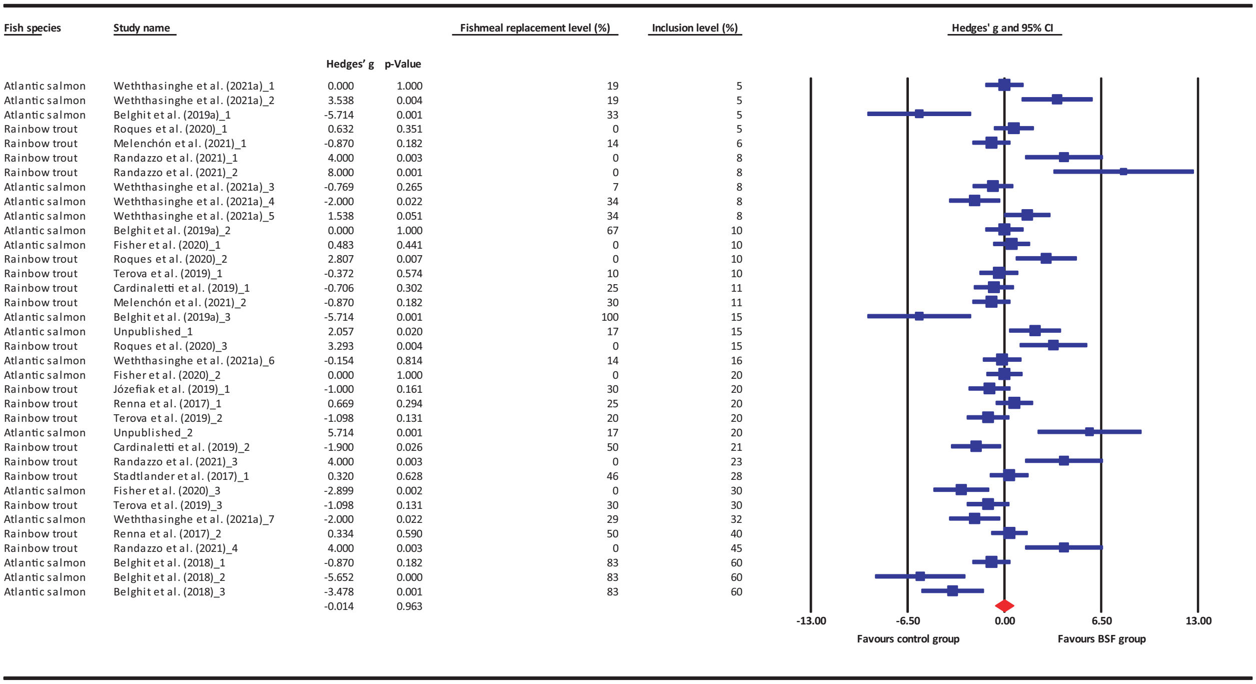
TABLE 1 (Continued)

Nutrient	Larvae		Prepupae		Pupae	
	Mean	SD	Mean	SD	Mean	SD
C18:2n6	14	6.7 (58)	6.7	3.4 (27)	5.2 (1)	
C18:3n3	1.5	0.8 (58)	3.9	6.9 (26)	0.7 (1)	
C20:4n6	0.4	0.5 (39)				
C20:5n3	1.1	1.5 (41)	0.1	0.1 (5)		
C22:6n3	0.7	0.9 (30)	0.1	0.2 (5)		

Note: Values in parentheses are the number of data points used for calculating the mean.

Sources for proximate and mineral compositions: BSF larvae,[13,57–65] BSF prepupae[61,65–69] and BSF pupae.[60,65] Sources for amino acid compositions: BSF larvae,[11–13,28,49,54,57,64,65,70–80] BSF pre-pupae[37,65,66,69,80–82] and BSF pupae.[65] Sources for fatty acid compositions: BSF larvae,[11,13,54,57,58,62,65,83–89] BSF pre-pupae[65,67–69,90–93] and BSF pupae.[65]

Abbreviation: SD, Standard deviation.



Fish species	Study name	Hedges' g	p-Value	Fishmeal replacement level (%)	Inclusion level (%)
Atlantic salmon	Weththasinghe et al. (2021a)_1	0.000	1.000	19	5
Atlantic salmon	Weththasinghe et al. (2021a)_2	3.538	0.004	19	5
Atlantic salmon	Belghit et al. (2019a)_1	-5.714	0.001	33	5
Rainbow trout	Roques et al. (2020)_1	0.632	0.351	0	5
Rainbow trout	Melenchón et al. (2021)_1	-0.870	0.182	14	6
Rainbow trout	Randazzo et al. (2021)_1	4.000	0.003	0	8
Rainbow trout	Randazzo et al. (2021)_2	8.000	0.001	0	8
Atlantic salmon	Weththasinghe et al. (2021a)_3	-0.769	0.265	7	8
Atlantic salmon	Weththasinghe et al. (2021a)_4	-2.000	0.022	34	8
Atlantic salmon	Weththasinghe et al. (2021a)_5	1.538	0.051	34	8
Atlantic salmon	Belghit et al. (2019a)_2	0.000	1.000	67	10
Atlantic salmon	Fisher et al. (2020)_1	0.483	0.441	0	10
Rainbow trout	Roques et al. (2020)_2	2.807	0.007	0	10
Rainbow trout	Terova et al. (2019)_1	-0.372	0.574	10	10
Rainbow trout	Cardinaletti et al. (2019)_1	-0.706	0.302	25	11
Rainbow trout	Melenchón et al. (2021)_2	-0.870	0.182	30	11
Atlantic salmon	Belghit et al. (2019a)_3	-5.714	0.001	100	15
Atlantic salmon	Unpublished_1	2.057	0.020	17	15
Rainbow trout	Roques et al. (2020)_3	3.293	0.004	0	15
Atlantic salmon	Weththasinghe et al. (2021a)_6	-0.154	0.814	14	16
Atlantic salmon	Fisher et al. (2020)_2	0.000	1.000	0	20
Rainbow trout	Józefiak et al. (2019)_1	-1.000	0.161	30	20
Rainbow trout	Renna et al. (2017)_1	0.669	0.294	25	20
Rainbow trout	Terova et al. (2019)_2	-1.098	0.131	20	20
Atlantic salmon	Unpublished_2	5.714	0.001	17	20
Rainbow trout	Cardinaletti et al. (2019)_2	-1.900	0.026	50	21
Rainbow trout	Randazzo et al. (2021)_3	4.000	0.003	0	23
Rainbow trout	Stadtlander et al. (2017)_1	0.320	0.628	46	28
Atlantic salmon	Fisher et al. (2020)_3	-2.899	0.002	0	30
Rainbow trout	Terova et al. (2019)_3	-1.098	0.131	30	30
Atlantic salmon	Weththasinghe et al. (2021a)_7	-2.000	0.022	29	32
Rainbow trout	Renna et al. (2017)_2	0.334	0.590	50	40
Rainbow trout	Randazzo et al. (2021)_4	4.000	0.003	0	45
Atlantic salmon	Belghit et al. (2018)_1	-0.870	0.182	83	60
Atlantic salmon	Belghit et al. (2018)_2	-5.652	0.000	83	60
Atlantic salmon	Belghit et al. (2018)_3	-3.478	0.001	83	60
		-0.014	0.963		

FIGURE 2 Forest plot of effect sizes (Hedges' g) of specific growth rate in salmonids between experimental diets containing black soldier fly (BSF) and control diets (full data set). The mean effect size, calculated according to a random effects model, is indicated by the red diamond at the bottom. The size of the blue squares illustrates the weight of each study relatively to the mean effect size. Smaller squares represent less weight. CI, Confidence interval

in SGR between the studies in the full data set. However, the other variables in the model including feed production method, BSF development stage, BSF processing method and fish body size did not explain heterogeneity at any significant level. The variables included in the meta-regression model could explain only 19% of the heterogeneity in SGR between studies (Table 2).

The meta-analyses of sub-data sets including salmon, salmon pre-smolts, rainbow trout, full-fat BSF and defatted BSF showed that, on average, the SGR of fish fed BSF diets did not differ from that of fish fed control diets. Three groups were identified according to the source(s) of protein replaced: 1) fishmeal, 2) fishmeal and plant protein sources and 3) non-fishmeal protein sources. The meta-analyses within these three groups showed that replacing fishmeal with BSF decreased SGR of salmonids, whereas replacement of both fishmeal and plant protein sources did not change SGR. The replacement of non-fishmeal protein sources with BSF even increased the SGR. The analyses further showed the presence of unexplained heterogeneity between the studies in all the sub-data sets. Nevertheless, there were no sufficient data to conduct further subgroup analyses or meta-regression in these data sets (Table 3).

Linear and quadratic regressions in the full data set and sub-data sets revealed no linear or quadratic relationships between the dietary inclusion level of BSF (Table S5) or dietary chitin level (Tables S6) and effect sizes of SGR. In the BSF larvae data set, however, SGR in salmonids tended ($p = 0.088$) to decrease linearly with increasing level of BSF in the diet. The fishmeal replacement level

TABLE 2 Heterogeneity in effect sizes (Hedges' g) and significance level (*p* value) of different categorical and continuous variables determined by meta-regression analysis

			p Value							
Parameter	Heterogeneity explained by the model (%)	Test of the model	Heterogeneity unexplained by the model	Fish species	Feed production	Type of protein source replaced	BSF development stage	BSF processing method	BSF inclusion level	Fish body size
SGR	0.19	***	***	**	NS	***	NS	NS	*	NS
FCR	0.02	**	***	NS	NS	**	NS	NS	NS	NS
Feed intake	−0.09	*	***	NS	NS	NS	NS	NS	*	NS

Abbreviations: BSF, Black soldier fly (*Hermetia illucens*); FCR, feed conversion ratio; SGR, specific growth rate.

Asterisks denote level of significance (NS: not significant, $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$).

had negative linear relationships and/or quadratic relationships with effect sizes of SGR in the full data set, as well as in sub-data sets including salmon, rainbow trout, BSF larvae, BSF prepupae/pupae and defatted BSF (Figure 3 and Table S7).

3.2 | Feed conversion ratio

The forest plot in Figure 4 shows the pooled effect of BSF inclusion in diets on FCR in salmonids. In the full data set of FCR, the Hedges' g, between BSF diets and control diets ranged from −8 to 4.8, with 80% of the comparisons showing a decrease or no change in FCR in fish fed BSF diets compared to control diets. The meta-analysis of FCR showed a mean effect size of 0.094 (Confidence interval: −0.341 to 0.529). On average, FCR in salmonids fed BSF diets did not differ from those fed the control diets. The test of heterogeneity, *Q*-value was 185.2 with a corresponding *p* value of <0.001, showing a significant heterogeneity in true effect sizes of FCR between the studies. Furthermore, the I^2 statistic showed that 74.1% of the observed heterogeneity was caused by the true effects rather than the sampling error. The variance of true effects (T^2) was 1.7 and the standard deviation of true effects (T) was 1.3.

According to the meta-regression, the protein source(s) replaced partially caused the heterogeneity in FCR between the studies in the full data set. However, the other variables in the model including fish species, feed production method, BSF development stage, BSF processing method, BSF inclusion level and fish body size did not explain heterogeneity at any significant level. The variables included in the meta-regression model could explain only 2% of the heterogeneity in FCR between studies (Table 2).

The salmon data set showed that, on average, dietary inclusion of BSF tended ($p = 0.095$) to increase FCR in salmon compared to control diets. The mean effect size for salmon pre-smolts showed an increased FCR in fish fed BSF diets compared to fish fed control diets. The meta-analysis of the FCR in rainbow trout group showed no statistically significant effect of BSF in the diet. The meta-analysis of the three groups categorized according to the type of protein source(s) replaced showed that replacing fishmeal with BSF did not change FCR of salmonids, whereas the replacement of both fishmeal and plant protein sources increased FCR and the replacement of non-fishmeal protein sources decreased FCR. The two sub-data sets sorted according to the processing method of BSF showed that feeding either full-fat or defatted BSF had no impact on FCR in salmonids. Although all the sub-data sets revealed the presence of unexplained heterogeneity between the studies, potential factors responsible for this could not be identified due to insufficient availability of data (Table 3).

Linear and quadratic regressions in the full data set and sub-data sets revealed that there were no linear or quadratic relationships between the inclusion level of BSF (Table S5) or chitin level in the diet (Table S6) and effect sizes of FCR. In the salmon data set, however, FCR tended ($p = 0.05$) to increase linearly with increasing level of BSF in the diet. Fishmeal replacement level on the other hand

TABLE 3 Effect sizes (Hedges' g) of growth performance and nutrient utilization data in salmonids between experimental diets containing black soldier fly (BSF) and control diets (sub-data sets)

				Random effect model			Heterogeneity		
Parameter	**Data subset**	**Number of studies**	**Number of comparisons**	**Hedges' g**	**95% CI**	***p***	**Q**	***p***	***I^2***
SGR	Species								
	Atlantic salmon	5	18	−0.72	−1.7 to 0.2	NS	91.9	***	81.5
	Rainbow trout	8	18	0.60	−0.2 to 1.4	NS	72.5	***	76.5
	Salmon life stage								
	Pre-smolt	4	15	−0.36	−1.3 to 0.6	NS	73.4	***	80.9
	Post-smolt	No sufficient data							
	Protein source(s) replaced								
	Fishmeal	7	14	−0.76	−1.4 to −0.2	*	29.7	**	56.2
	Fishmeal + Plant protein	3	12	−0.25	−1.4 to 0.9	NS	64.1	***	82.8
	Non-fishmeal	3	10	1.98	0.5 to 3.4	**	51.2	***	82.4
	BSF processing method								
	Full-fat	6	16	−0.37	−1.1 to 0.3	NS	50.3	***	70.2
	Defatted	8	20	0.26	−0.7 to 1.2	NS	113	***	83.1
FCR	Species								
	Atlantic salmon	6	23	0.51	−0.1 to 1.1	NS	77.4	***	71.6
	Rainbow trout	11	26	−0.31	−0.9 to 0.3	NS	104	***	76.1
	Salmon life stage								
	Pre-smolt	4	15	1.01	0.3 to 1.7	**	47.6	***	70.6
	Post-smolt	No sufficient data							
	Protein source(s) replaced								
	Fishmeal	11	27	0.18	−0.3 to 0.6	NS	71.4	***	63.6
	Fishmeal + Plant protein	3	12	1.11	0.3 to 1.9	**	36.8	***	70.1
	Non-fishmeal	3	10	−1.89	−3.3 to −0.5	**	49.2	***	81.7
	BSF processing method								
	Full-fat	9	25	0.37	−0.1 to 0.9	NS	74.2	***	67.7
	Defatted	10	24	−0.30	−1.0 to 0.4	NS	109	***	78.9
Feed intake	Species								
	Atlantic salmon	6	23	−0.01	−0.5 to 0.5	NS	55.7	***	60.5
	Rainbow trout	11	27	−0.18	−0.7 to 0.4	NS	90.6	***	71.3
	Salmon life stage								
	Pre-smolt	4	15	0.08	−0.3 to 0.5	NS	21.2	NS	33.9
	Post-smolt	No sufficient data							
	Protein source(s) replaced								
	Fishmeal	11	28	−0.70	−1.3 to −0.1	*	103	***	73.9
	Fishmeal + Plant protein	3	12	0.12	−0.4 to 0.7	NS	21.1	*	48.0
	Non-fishmeal	3	10	0.51	−0.1 to 1.1	NS	16.4	NS	45.0
	BSF processing method								
	Full-fat	9	25	−0.49	−1.1 to 0.1	NS	82.2	***	70.8

(Continues)

TABLE 3 (Continued)

				Random effect model			Heterogeneity		
Parameter	**Data subset**	**Number of studies**	**Number of comparisons**	**Hedges' g**	**95% CI**	***p***	**Q**	***p***	**I^2**
	Defatted	10	25	0.21	−0.3 to 0.7	NS	62.1	***	61.4
ADC of protein	Species								
	Atlantic salmon	4	13	−1.03	−1.7 to −0.4	**	28.7	**	58.2
	Rainbow trout	No sufficient data							
	BSF development stage								
	Larvae	6	16	−0.73	−1.4 to −0.1	*	45.2	***	66.8
	Prepupae/pupae	No sufficient data							
	BSF processing method								
	Full-fat	3	11	−0.52	−1.4 to 0.3	NS	36.7	***	72.2
	Defatted	No sufficient data							
	Feed production method								
	Extrusion	5	15	−0.79	−1.5 to −0.1	*	44.4	***	68.5
	Pelleting	No sufficient data							
PER	Species								
	Atlantic salmon	4	15	−0.19	−1.0 to 0.7	NS	63.1	***	77.8
	Rainbow trout	No sufficient data							
	BSF processing method								
	Full-fat	5	14	−0.33	−1.0 to 0.4	NS	41.2	***	68.5
	Defatted	No sufficient data							

Abbreviations: ADC of protein, apparent digestibility of protein; CI, Confidence interval; FCR, feed conversion ratio; PER, protein efficiency ratio; SGR, specific growth rate.

Asterisks denote level of significance (NS, not significant, $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$).

had both positive linear relationships and quadratic relationships with the effect size of FCR in the full data set, and the sub-data sets including rainbow trout, BSF prepupae/pupae and defatted BSF (Figure 5 and Table S7).

3.3 | Feed intake

The forest plot in Figure 6 shows the pooled effect of BSF inclusion in diets on feed intake in salmonids. In the full data set of feed intake, the Hedges' g, between BSF diets and control diets ranged from −27 to 4.5, with 78% of the comparisons showing an increase or no change in feed intake in fish fed BSF diets compared to control diets. The meta-analysis of feed intake showed a mean effect size of −0.099 (Confidence interval: −0.476 to 0.277). On average, the feed intake in salmonids fed BSF diets did not differ from those fed the control diets. The test of heterogeneity, *Q*-value was 146.4 with a corresponding *p* value of <0.001, showing a significant heterogeneity in true effect sizes of feed intake between the studies. Furthermore, the I^2 statistic showed that 66.5% of the observed heterogeneity was caused by the true effects rather than the sampling error. The variance of true effects (T^2) was 1.1 and the standard deviation of true effects (*T*) was 1.1.

According to the meta-regression, BSF inclusion level partially caused the heterogeneity in feed intake between the studies in the full data set. However, the other variables in the model did not explain heterogeneity at any significant level (Table 2). The sub-data sets showed that, on average, feed intake did not differ between fish fed BSF diets and control diets, except replacing fishmeal with BSF decreased feed intake and replacing non-fishmeal protein sources tended ($p = 0.095$) to increase feed intake of salmonids (Table 3).

Linear and quadratic regressions in the full data set and sub-data sets revealed that there were no linear or quadratic relationships between the inclusion level of BSF (Table S5) or chitin level in the diet (Table S6) and effect sizes of feed intake. Fishmeal replacement level on the other hand had negative linear relationships and/or quadratic relationships with the effect size of feed intake in the full data set, and the sub-data sets including salmon, BSF larvae, full-fat BSF and defatted BSF (Figure 7 and Table S7).

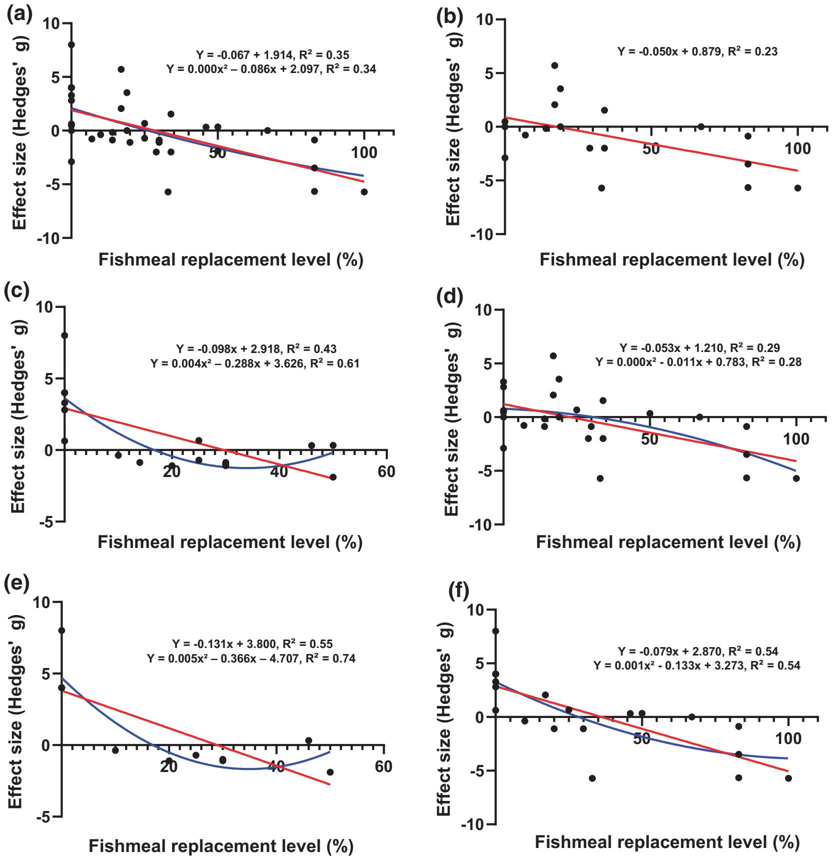


FIGURE 3 The relationship between the fishmeal replacement level by black soldier fly and the effect sizes (Hedges' g) of specific growth rate for the full data set (a), salmon data set (b), rainbow trout data set (c), black soldier fly larvae data set (d), black soldier fly prepupae/pupae data set (e) and defatted black soldier fly data set (f). Red lines represent linear relationships and blue lines represent quadratic relationships

3.4 | Protein digestibility

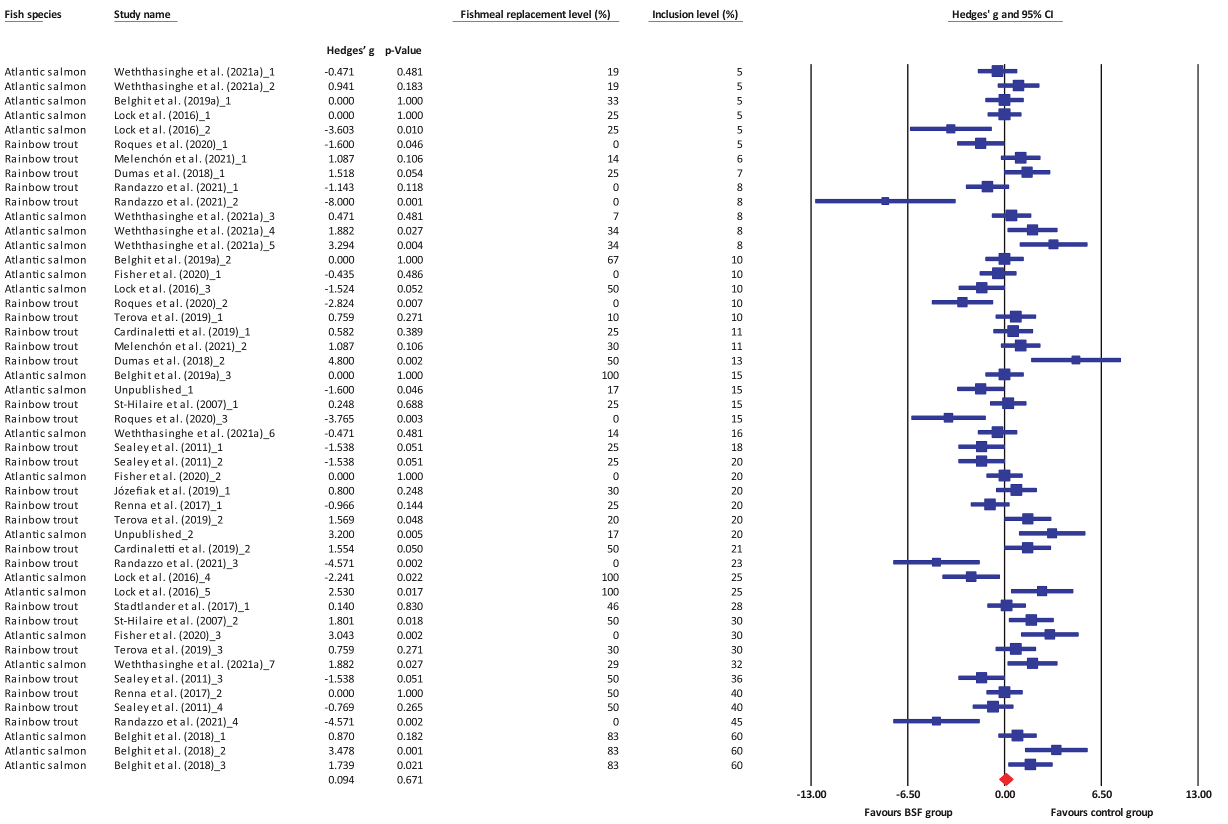
The forest plot in Figure 8 shows the pooled effect of BSF inclusion in diets on ADC of protein in salmonids. In the full data set, the Hedges' g, between BSF diets and control diets ranged from −3.30 to 1.43, with 74% of the comparisons showing no change in ADC of protein in fish fed BSF diets compared to control diet. The meta-analysis of ADC of protein in the full data set showed a mean effect size of −0.540 (Confidence interval: −1.096 to 0.017). On average, the dietary inclusion of BSF tended ($p = 0.057$) to decrease ADC of protein in salmonids compared to control diets. The test of heterogeneity, Q-value was 49.3 with a corresponding p value of <0.001, showing a significant heterogeneity in true effect sizes of ADC of protein between the studies. Furthermore, the I^2 statistic indicates that 63.5% of the observed heterogeneity was caused by the true effects rather than the sampling error. The variance of true effects (T^2) was 0.9 and the standard deviation of true effects (T) was 1.0.

For salmon, BSF larvae and extruded feed data sets, the mean effect sizes of ADC of protein showed that dietary inclusion of BSF decreased ADC of protein compared to control diets. The full-fat BSF data set showed no difference in ADC of protein between BSF and control groups (Table 3). There were no sufficient data available for other subgroups to conduct meta-analysis.

Linear and quadratic regressions in the full data set revealed that there were no significant linear or quadratic relationships between the dietary inclusion level of BSF (Tables S5), dietary chitin level (Tables S6) or fishmeal replacement level (Table S7) and effect sizes of ADC of protein.

3.5 | Protein efficiency ratio

The forest plot in Figure 9 shows the pooled effect of BSF inclusion in diets on PER in salmonids. In the full data set of PER, the Hedges' g, between BSF diets and control diets ranged from −4.8 to 3.4, with 76% of the comparisons showing an increase or no change in PER in fish fed BSF diets compared to control diet. The meta-analysis of PER in the full data set showed a mean effect size of −0.064 (Confidence interval: −0.655 to 0.526). On average, the PER in salmonids fed BSF diets did not differ from those fed the control diets. The test of heterogeneity, Q-value was 68.9 with a corresponding p value of <0.001, showing a significant heterogeneity in true effect sizes of PER between the studies. Furthermore, the I^2 statistic showed that 71% of the observed heterogeneity was caused by the true effects rather than the sampling error. The variance of true effects (T^2) was 1.3 and the standard deviation of true effects (T) was 1.1.



Fish species	Study name	Hedges' g	p-Value	Fishmeal replacement level (%)	Inclusion level (%)
Atlantic salmon	Weththasinghe et al. (2021a)_1	-0.471	0.481	19	5
Atlantic salmon	Weththasinghe et al. (2021a)_2	0.941	0.183	19	5
Atlantic salmon	Belghit et al. (2019a)_1	0.000	1.000	33	5
Atlantic salmon	Lock et al. (2016)_1	0.000	1.000	25	5
Atlantic salmon	Lock et al. (2016)_2	-3.603	0.010	25	5
Rainbow trout	Roques et al. (2020)_1	-1.600	0.046	0	5
Rainbow trout	Melenchón et al. (2021)_1	1.087	0.106	14	6
Rainbow trout	Dumas et al. (2018)_1	1.518	0.054	25	7
Rainbow trout	Randazzo et al. (2021)_1	-1.143	0.118	0	8
Rainbow trout	Randazzo et al. (2021)_2	-8.000	0.001	0	8
Atlantic salmon	Weththasinghe et al. (2021a)_3	0.471	0.481	7	8
Atlantic salmon	Weththasinghe et al. (2021a)_4	1.882	0.027	34	8
Atlantic salmon	Weththasinghe et al. (2021a)_5	3.294	0.004	34	8
Atlantic salmon	Belghit et al. (2019a)_2	0.000	1.000	67	10
Atlantic salmon	Fisher et al. (2020)_1	-0.435	0.486	0	10
Atlantic salmon	Lock et al. (2016)_3	-1.524	0.052	50	10
Rainbow trout	Roques et al. (2020)_2	-2.824	0.007	0	10
Rainbow trout	Terova et al. (2019)_1	0.759	0.271	10	10
Rainbow trout	Cardinaletti et al. (2019)_1	0.582	0.389	25	11
Rainbow trout	Melenchón et al. (2021)_2	1.087	0.106	30	11
Rainbow trout	Dumas et al. (2018)_2	4.800	0.002	50	13
Atlantic salmon	Belghit et al. (2019a)_3	0.000	1.000	100	15
Atlantic salmon	Unpublished_1	-1.600	0.046	17	15
Rainbow trout	St-Hilaire et al. (2007)_1	0.248	0.688	25	15
Rainbow trout	Roques et al. (2020)_3	-3.765	0.003	0	15
Atlantic salmon	Weththasinghe et al. (2021a)_6	-0.471	0.481	14	16
Rainbow trout	Sealey et al. (2011)_1	-1.538	0.051	25	18
Rainbow trout	Sealey et al. (2011)_2	-1.538	0.051	25	20
Atlantic salmon	Fisher et al. (2020)_2	0.000	1.000	0	20
Rainbow trout	Józefiak et al. (2019)_1	0.800	0.248	30	20
Rainbow trout	Renna et al. (2017)_1	-0.966	0.144	25	20
Rainbow trout	Terova et al. (2019)_2	1.569	0.048	20	20
Atlantic salmon	Unpublished_2	3.200	0.005	17	20
Rainbow trout	Cardinaletti et al. (2019)_2	1.554	0.050	50	21
Rainbow trout	Randazzo et al. (2021)_3	-4.571	0.002	0	23
Atlantic salmon	Lock et al. (2016)_4	-2.241	0.022	100	25
Atlantic salmon	Lock et al. (2016)_5	2.530	0.017	100	25
Rainbow trout	Stadtlander et al. (2017)_1	0.140	0.830	46	28
Rainbow trout	St-Hilaire et al. (2007)_2	1.801	0.018	50	30
Atlantic salmon	Fisher et al. (2020)_3	3.043	0.002	0	30
Rainbow trout	Terova et al. (2019)_3	0.759	0.271	30	30
Atlantic salmon	Weththasinghe et al. (2021a)_7	1.882	0.027	29	32
Rainbow trout	Sealey et al. (2011)_3	-1.538	0.051	50	36
Rainbow trout	Renna et al. (2017)_2	0.000	1.000	50	40
Rainbow trout	Sealey et al. (2011)_4	-0.769	0.265	50	40
Rainbow trout	Randazzo et al. (2021)_4	-4.571	0.002	0	45
Atlantic salmon	Belghit et al. (2018)_1	0.870	0.182	83	60
Atlantic salmon	Belghit et al. (2018)_2	3.478	0.001	83	60
Atlantic salmon	Belghit et al. (2018)_3	1.739	0.021	83	60
		0.094	0.671		

FIGURE 4 Forest plot of effect sizes (Hedges' g) of feed conversion ratio in salmonids between experimental diets containing black soldier fly (BSF) and control diets (full data set). The mean effect size, calculated according to a random effects model, is indicated by the red diamond at the bottom. The size of the blue squares illustrates the weight of each study relatively to the mean effect size. Smaller squares represent less weight. CI, Confidence interval

For salmon and full-fat BSF data sets, the mean effect sizes of PER showed that dietary inclusion of BSF had no impact on PER compared to control diets (Table 3). There were no sufficient data available for other groups to conduct meta-analysis.

Linear and quadratic regressions in the full data set revealed that there were no significant linear or quadratic relationships between the dietary inclusion level of BSF (Tables S5), dietary chitin level (Tables S6) or fishmeal replacement level (Table S7) and effect sizes of PER.

4 | DISCUSSION

The present meta-analysis provided an overall insight into the direction of effects obtained across studies that used BSF in diets for Atlantic salmon and rainbow trout. The control diets in the present data set contained fishmeal, plant and land animal protein sources. Majority of the individual BSF containing experimental diets in the full data set (>75%) of the present meta-analysis supported similar or superior growth rate, feed utilization and feed intake in salmonids compared to the respective control diets. However, the mean effect sizes for the full data set revealed no differences in growth rate and feed conversion between the fish fed BSF diets and control diets. This was accompanied by the mean effect size for feed intake, showing no difference between BSF and control diets-fed fish. Hence, the use of 5–60% BSF in salmonid diets replacing fishmeal, plant and animal protein is possible without compromising growth performance. It is possible that the mean effect sizes in the meta-analysis averaged out the possible factors influencing the effectiveness of dietary BSF in salmonids.[17] The wide range of effect sizes of SGR, FCR and feed intake in the present analysis indicated the variation in the effectiveness of the use of BSF meal in diets for salmonids. The heterogeneity test also confirmed the possible effect of influencing factors and meta-regression was used to identify these factors in the present study.

Previous reviews showed that different fish species responded differently to dietary BSF.[19,29] In accordance, the present study also showed that the type of salmonid species was partially responsible for the heterogeneity of growth rate in salmonids between the studies. This confirmed the importance of conducting meta-analysis for salmon and rainbow trout separately. Separate meta-analyses for each fish species also showed that the use of BSF in diets in the form of either full-fat or defatted had no impact on growth rate, feed utilization and feed intake. However, further analysis revealed that the dietary

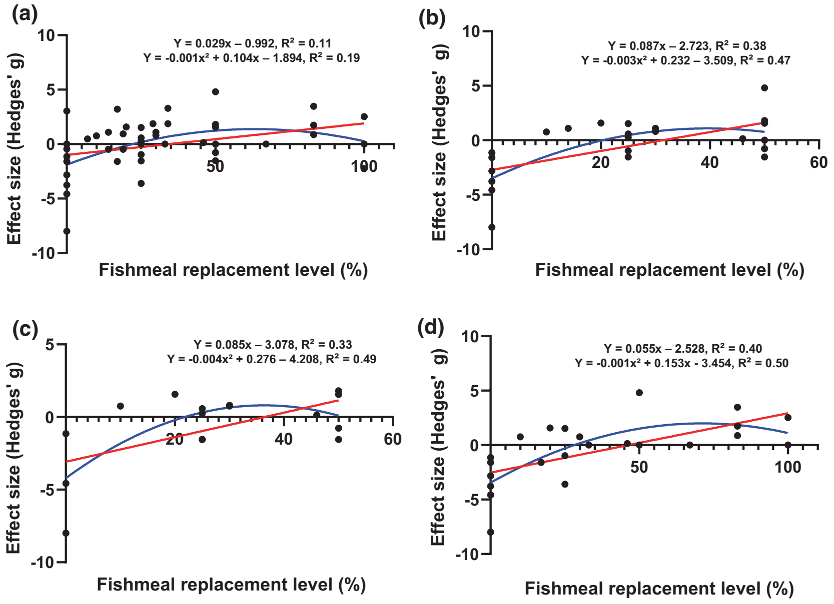


FIGURE 5 The relationship between the fishmeal replacement level by black soldier fly and the effect sizes (Hedges' g) of feed conversion ratio for the full data set (a), rainbow trout data set (b), black soldier fly prepupae/pupae data set (c) and defatted black soldier fly data set (d). Red lines represent linear relationships and blue lines represent quadratic relationships

Fish species	Study name	Fishmeal replacement level (%)	Inclusion level (%)	Hedges's g	p-Value
Atlantic salmon	Belghit et al. (2019)_1	33	5	0.000	1.000
Atlantic salmon	Lock et al. (2016)_1	25	5	1.600	0.047
Atlantic salmon	Lock et al. (2016)_2	25	5	-13.143	0.005
Rainbow trout	Roques et al. (2020)_1	0	5	-0.267	0.685
Atlantic salmon	Weththasinghe et al. (2021b)_1	19	5	0.000	1.000
Atlantic salmon	Weththasinghe et al. (2021b)_2	19	5	1.350	0.076
Rainbow trout	Melenchón et al. (2020)_1	14	6	0.000	1.000
Rainbow trout	Dumas et al. (2018)_1	25	7	-1.067	0.140
Rainbow trout	Randazzo et al. (2021)_1	0	8	0.400	0.546
Rainbow trout	Randazzo et al. (2021)_2	0	8	0.800	0.248
Atlantic salmon	Weththasinghe et al. (2021b)_3	7	8	-0.388	0.558
Atlantic salmon	Weththasinghe et al. (2021b)_4	34	8	-0.530	0.430
Atlantic salmon	Weththasinghe et al. (2021b)_5	34	8	1.012	0.157
Atlantic salmon	Belghit et al. (2019)_2	67	10	0.000	1.000
Atlantic salmon	Fisher et al. (2020)_1	0	10	0.145	0.814
Atlantic salmon	Lock et al. (2016)_3	50	10	-3.886	0.009
Rainbow trout	Roques et al. (2020)_2	0	10	3.600	0.003
Rainbow trout	Terova et al. (2019)_1	10	10	0.533	0.427
Rainbow trout	Cardinaletti et al. (2019)_1	25	11	0.686	0.315
Rainbow trout	Melenchón et al. (2020)_2	30	11	-0.373	0.549
Rainbow trout	Dumas et al. (2018)_2	50	13	-0.533	0.427
Atlantic salmon	Belghit et al. (2019)_3	100	15	0.000	1.000
Rainbow trout	Roques et al. (2020)_3	0	15	3.733	0.003
Rainbow trout	St?Hilaire et al. (2007)_1	25	15	-2.733	0.003
Atlantic salmon	Unpublished_1	17	15	4.480	0.002
Atlantic salmon	Weththasinghe et al. (2021b)_6	14	16	0.000	1.000
Rainbow trout	Sealey et al. (2011)_1	25	18	-15.840	0.001
Atlantic salmon	Fisher et al. (2020)_2	0	20	0.000	1.000
Rainbow trout	Józefiak et al. (2019)_1	30	20	0.500	0.455
Rainbow trout	Renna et al. (2017)_1	25	20	0.373	0.549
Rainbow trout	Sealey et al. (2011)_2	25	20	-11.680	0.001
Rainbow trout	Terova et al. (2019)_2	20	20	0.933	0.187
Atlantic salmon	Unpublished_2	17	20	0.707	0.302
Rainbow trout	Cardinaletti et al. (2019)_2	50	21	0.000	1.000
Rainbow trout	Randazzo et al. (2021)_3	0	23	0.200	0.760
Atlantic salmon	Lock et al. (2016)_4	100	25	-12.229	0.005
Atlantic salmon	Lock et al. (2016)_5	100	25	-26.743	0.005
Rainbow trout	Dumas et al. (2018)_3	100	26	-2.000	0.022
Rainbow trout	Stadtlander et al. (2017)_1	46	28	0.300	0.649
Atlantic salmon	Fisher et al. (2020)_3	0	30	0.000	1.000
Rainbow trout	St?Hilaire et al. (2007)_2	50	30	-1.863	0.016
Rainbow trout	Terova et al. (2019)_3	30	30	1.333	0.079
Atlantic salmon	Weththasinghe et al. (2021b)_7	29	32	-0.446	0.503
Rainbow trout	Sealey et al. (2011)_3	50	36	-6.880	0.001
Rainbow trout	Renna et al. (2017)_2	50	40	0.000	1.000
Rainbow trout	Sealey et al. (2011)_4	50	40	-2.400	0.012
Rainbow trout	Randazzo et al. (2021)_4	0	45	0.200	0.760
Atlantic salmon	Belghit et al. (2018)_1	83	60	0.000	1.000
Atlantic salmon	Belghit et al. (2018)_2	83	60	-0.435	0.486
Atlantic salmon	Belghit et al. (2018)_3	83	60	-1.304	0.061
				-0.099	0.605

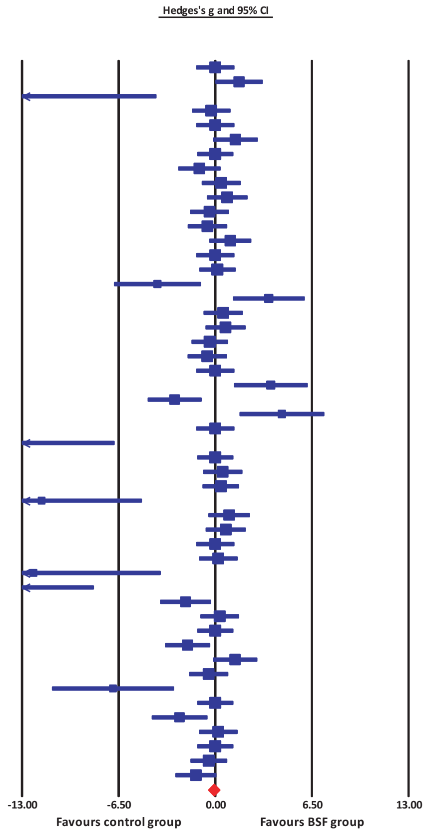


FIGURE 6 Forest plot of effect sizes (Hedges' g) of feed intake in salmonids between experimental diets containing black soldier fly (BSF) and control diets (full data set). The mean effect size, calculated according to a random effects model, is indicated by the red diamond at the bottom. The size of the blue squares illustrates the weight of each study relatively to the mean effect size. Smaller squares represent less weight. CI, Confidence interval

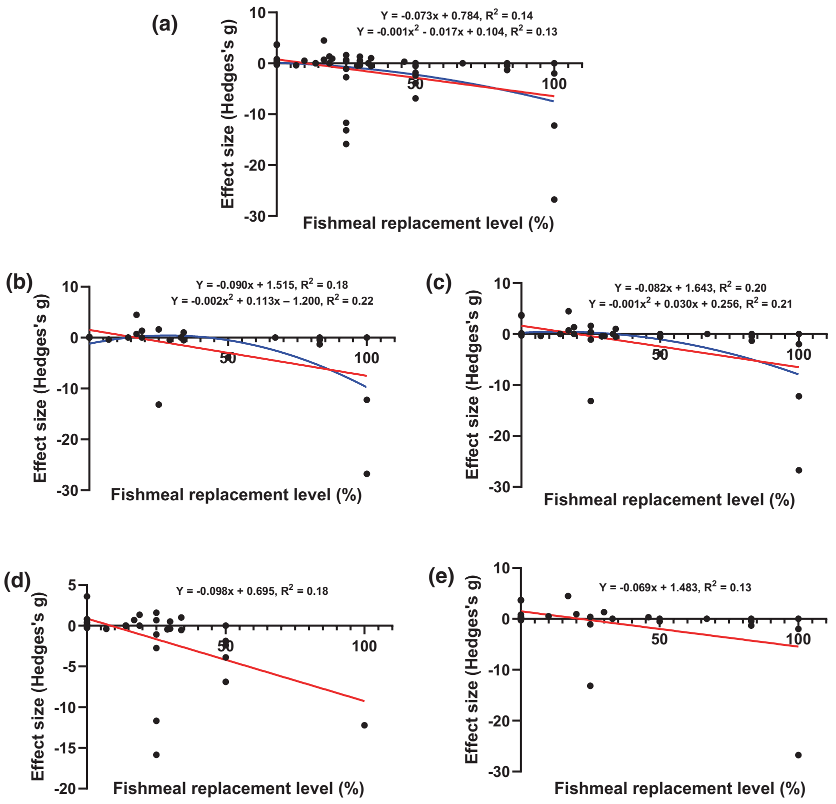
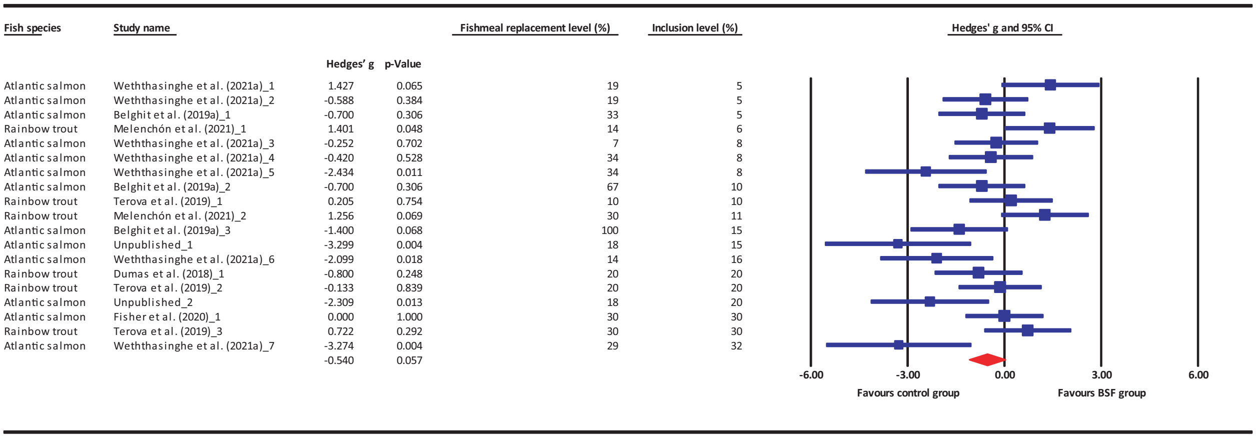


FIGURE 7 The relationship between the fishmeal replacement level by black soldier fly and the effect sizes (Hedges' g) of feed intake for the full data set (a), salmon data set (b), black soldier fly larvae data set (c), full-fat black soldier fly data set (d) and defatted black soldier fly data set (e). Red lines represent linear relationships and blue lines represent quadratic relationships

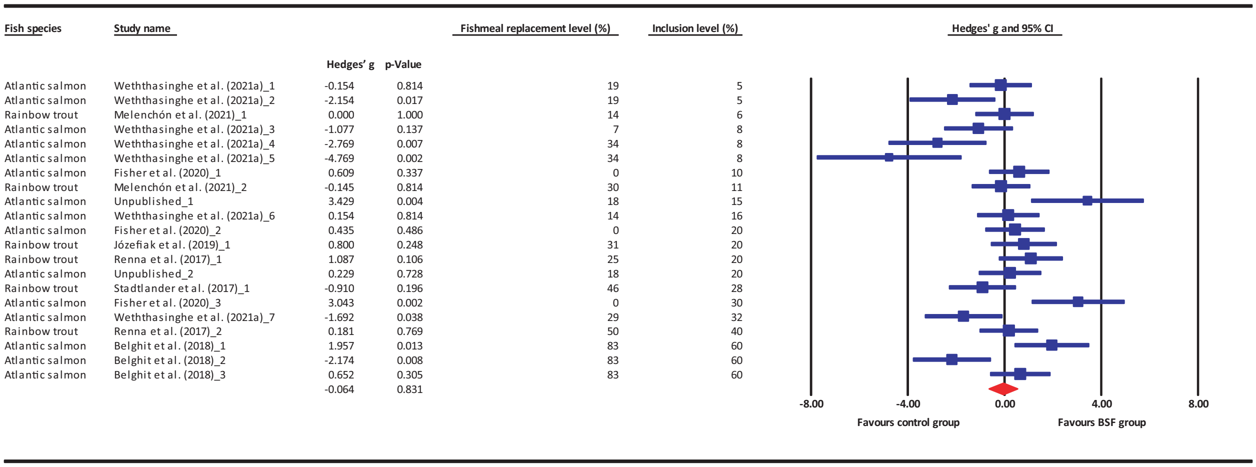


Fish species	Study name	Hedges' g	p-Value	Fishmeal replacement level (%)	Inclusion level (%)
Atlantic salmon	Weththasinghe et al. (2021a)_1	1.427	0.065	19	5
Atlantic salmon	Weththasinghe et al. (2021a)_2	-0.588	0.384	19	5
Atlantic salmon	Belghit et al. (2019a)_1	-0.700	0.306	33	5
Rainbow trout	Melenchón et al. (2021)_1	1.401	0.048	14	6
Atlantic salmon	Weththasinghe et al. (2021a)_3	-0.252	0.702	7	8
Atlantic salmon	Weththasinghe et al. (2021a)_4	-0.420	0.528	34	8
Atlantic salmon	Weththasinghe et al. (2021a)_5	-2.434	0.011	34	8
Atlantic salmon	Belghit et al. (2019a)_2	-0.700	0.306	67	10
Rainbow trout	Terova et al. (2019)_1	0.205	0.754	10	10
Rainbow trout	Melenchón et al. (2021)_2	1.256	0.069	30	11
Atlantic salmon	Belghit et al. (2019a)_3	-1.400	0.068	100	15
Atlantic salmon	Unpublished_1	-3.299	0.004	18	15
Atlantic salmon	Weththasinghe et al. (2021a)_6	-2.099	0.018	14	16
Rainbow trout	Dumas et al. (2018)_1	-0.800	0.248	20	20
Rainbow trout	Terova et al. (2019)_2	-0.133	0.839	20	20
Atlantic salmon	Unpublished_2	-2.309	0.013	18	20
Atlantic salmon	Fisher et al. (2020)_1	0.000	1.000	30	30
Rainbow trout	Terova et al. (2019)_3	0.722	0.292	30	30
Atlantic salmon	Weththasinghe et al. (2021a)_7	-3.274	0.004	29	32
		-0.540	0.057		

FIGURE 8 Forest plot of effect sizes (Hedges' g) of apparent digestibility coefficient of protein in salmonids between experimental diets containing black soldier fly (BSF) and control diets (full dataset). The mean effect size, calculated according to a random effects model, is indicated by the red diamond at the bottom. The size of the blue squares illustrates the weight of each study relatively to the mean effect size. Smaller squares represent less weight. CI, Confidence interval

inclusion of BSF depressed the feed utilization in salmon pre-smolts, indicating low utilization of BSF for salmon reared in freshwater.

As shown in Table S8, the nutrient composition of BSF varies with the processing methods. In a recent review, English et al.[16] also showed that the quality and nutritional composition of BSF can change dramatically based on processing. The processing method of insect meals is a crucial point that can have a direct effect on the growth performance and feed efficiency in fish.[30] In a previous study, growth performance of salmon differed by how the BSF was processed.[31] In addition, Basto et al.[32] reported that defatted BSF meal improved the digestibility of protein and amino acids compared to full-fat meal in European sea bass (*Dicentrarchus labrax*)



Fish species	Study name	Hedges' g	p-Value	Fishmeal replacement level (%)	Inclusion level (%)
Atlantic salmon	Weththasinghe et al. (2021a)_1	-0.154	0.814	19	5
Atlantic salmon	Weththasinghe et al. (2021a)_2	-2.154	0.017	19	5
Rainbow trout	Melenchón et al. (2021)_1	0.000	1.000	14	6
Atlantic salmon	Weththasinghe et al. (2021a)_3	-1.077	0.137	7	8
Atlantic salmon	Weththasinghe et al. (2021a)_4	-2.769	0.007	34	8
Atlantic salmon	Weththasinghe et al. (2021a)_5	-4.769	0.002	34	8
Atlantic salmon	Fisher et al. (2020)_1	0.609	0.337	0	10
Rainbow trout	Melenchón et al. (2021)_2	-0.145	0.814	30	11
Atlantic salmon	Unpublished_1	3.429	0.004	18	15
Atlantic salmon	Weththasinghe et al. (2021a)_6	0.154	0.814	14	16
Atlantic salmon	Fisher et al. (2020)_2	0.435	0.486	0	20
Rainbow trout	Józefiak et al. (2019)_1	0.800	0.248	31	20
Rainbow trout	Renna et al. (2017)_1	1.087	0.106	25	20
Atlantic salmon	Unpublished_2	0.229	0.728	18	20
Rainbow trout	Stadtlander et al. (2017)_1	-0.910	0.196	46	28
Atlantic salmon	Fisher et al. (2020)_3	3.043	0.002	0	30
Atlantic salmon	Weththasinghe et al. (2021a)_7	-1.692	0.038	29	32
Rainbow trout	Renna et al. (2017)_2	0.181	0.769	50	40
Atlantic salmon	Belghit et al. (2018)_1	1.957	0.013	83	60
Atlantic salmon	Belghit et al. (2018)_2	-2.174	0.008	83	60
Atlantic salmon	Belghit et al. (2018)_3	0.652	0.305	83	60
		-0.064	0.831		

FIGURE 9 Forest plot of effect sizes (Hedges' g) of protein efficiency ratio in salmonids between experimental diets containing black soldier fly (BSF) and control diets (full data set). The mean effect size, calculated according to a random effects model, is indicated by the red diamond at the bottom. The size of the blue squares illustrates the weight of each study relatively to the mean effect size. Smaller squares represent less weight. CI, Confidence interval

juveniles. On the contrary, present results showed that processing method of BSF (full-fat vs. defatted) did not cause heterogeneity in the growth performance of salmonids between the studies. The growth performances of salmonids fed BSF, on average, were similar to those fed control diets despite the BSF was in full-fat or defatted form. The meta-analysis conducted by Hua[17] showed that full-fat and defatted BSF meals affect SGR of fish similarly when only the nutrient-balanced diets were included in the data set. Although present and previous meta-analyses showed no differences in fish responses to the use of defatted and full-fat BSF in the diet, these results should be interpreted with caution because the diets in the data sets contained BSF with varying degrees of defatting (partially or fully defatted).

Feed production technologies such as extrusion might affect the nutritional values of feeds containing insect meals.[17] The processing method of feed (pelleting vs. extrusion) was reported to affect the responses of fish to dietary changes.[33–35] For instance, fish fed extruded diets had higher weight gain at low dietary protein levels[34] and higher nutrient utilization[35] than pelleted feeds. When the low-fishmeal diets were supplemented with enzymes, pelleted feed, but not extruded feed, improved fish growth and nutrient utilization.[33] On the contrary, present results showed that the feed production method did not explain the heterogeneity of SGR, FCR and feed intake in fish fed BSF across the studies. Additionally, the developmental stage of BSF did not contribute to the heterogeneity between the studies, even though the nutrient composition varied with the developmental stage of BSF. This indicates that differences in nutrient composition during BSF stages may not be sufficiently large enough to have an impact on fish growth performance.

The meta-analysis conducted by Hua[17] demonstrated that the use of up to 29% BSF meals in diets had no adverse effect on fish growth rate in comparison with control diets with similar nutrient content, but decreased at higher levels. Liland et al.[18] observed a linear reduction in SGR of fish and shellfish species used in aquaculture with increasing BSF level in the diet. In the present study, the growth performance parameters in salmonids did not show any linear or quadratic relationships with BSF inclusion level. Furthermore, there was no clear breaking point detected for both SGR and FCR with the increasing level of BSF in the diet of salmonids (data not shown). Nevertheless, dietary level of BSF could partially explain the heterogeneity of SGR and feed intake in salmonids existing across the studies used. In addition, BSF larvae data set showed a tendency to reduce SGR linearly with increasing dietary BSF level. When only salmon was considered in the analysis, increasing dietary level of BSF also tended to increase FCR linearly ($R^2 = 0.14$ and $p = 0.05$).

As indicated by the meta-regression for growth performance parameters, the effects of the types of protein source(s) replaced by BSF is worth further investigation. Thus, meta-analysis was conducted in the sub-data sets sorted according to the protein source(s) replaced by BSF. The replacement of fishmeal by BSF negatively affected the growth rate and feed intake in salmonids but did not affect the FCR. Although the replacement of fishmeal and plant protein sources with BSF did not affect SGR and feed intake of salmonids, it increased FCR. The replacement of non-fishmeal protein sources with BSF even increased the growth rate, as well as reduced FCR in salmonids. Hence, the present results strengthened the importance of the type of protein source(s) replaced by BSF when evaluating the nutritional values of BSF in salmonids. The fishmeal replacement levels in the studies included in the present meta-analysis ranged from 0% to 100%. The linear regression analysis showed that the increasing fishmeal replacement by BSF negatively affected the SGR, FCR and feed intake in salmonids. All the sub-data sets, except the full-fat BSF data set, also showed linear decrease in SGR with increasing level of fishmeal replacement. Similarly, FCR in fish increased linearly with increasing level of fishmeal replacement in rainbow trout, defatted BSF and BSF prepupae/pupae data sets. Such linear reductions were also observed for feed intake in salmon, BSF larvae, full-fat and defatted BSF data sets. As stressed by Hua and Bureau,[36] fishmeal replacement level might not be an objective parameter in evaluating nutritive values of alternative ingredients such as insect meals because the composition and nutritional value of fishmeal can vary widely. However, it can still provide a good indication on the dose response of fish for the replacement level of fishmeal in the diet.

All studies used in the present meta-analysis had balanced essential amino acid composition between the control and BSF diets, except one study that did not report any information regarding the amino acid profiles of diets or supplementation of amino acids.[37] Hence, the differences in fish responses according to the replaced protein source(s) were likely a reflection of the true differences between the nutritional values of the BSF and other protein sources rather than an artefact of discrepancies in the dietary amino acid profiles. It is possible that the depressed growth performance of salmonids fed diets replacing fishmeal might be due to limiting digestible amino acids in BSF compared to fishmeal. This illustrates the importance of determining the digestible protein, amino acids and energy levels in both the control diet and the test ingredient. The studies used in the present meta-analysis did not report any consideration of digestible amino acids in diet formulations. In literature, limited information is available on protein and amino acid digestibility of BSF in salmonids. The protein digestibility coefficient of BSF larvae meal was reported as 89% in Atlantic salmon[12] and 85% in rainbow trout.[14] Fisher et al.[12] further showed that the protein digestibility of BSF was lower than soybean meal (96%) and higher than corn protein concentrate (85%). In addition, Dumas et al.[14] reported that the digestibility of essential amino acids in BSF larvae meal varied from 84% to 96% in rainbow trout, while the digestibility of conditionally essential amino acid-like taurine was 57%. In these two studies, faeces were collected for digestibility estimation using faecal collection columns attached to the tanks. This might overestimate the protein digestibility compared to other faecal collection methods such as stripping, due to leaching of nitrogen (N) depending on the type of feed as explained by Shomorin et al.[38] Fishmeal may contain nutritional components that promote fish growth beyond the digestible nutrient content alone, such as taurine and low molecular weight compounds.[39–41] These components may be lacking in diets containing other protein sources and lead to better growth performance when such protein sources were replaced by BSF as explained in the review by Collins et al.[42] The growth reduction when fishmeal was replaced by BSF can also be due to decreased feed intake. However, the fishmeal replaced data set contained two studies which gave comparatively lower effect sizes for feed intake than the other studies.[31,43] It is, thus, possible that these two studies might influence the overall results for feed intake in this group. The improved growth in non-fishmeal replaced group can also be related to feed intake, as there was a tendency to increase in feed intake in this group.

As observed for growth performance data, the present study also showed that majority of the experimental diets containing BSF in literature gave similar protein digestibility and PER in salmonids as the control diets. Furthermore, the meta-analysis showed that, on average, the dietary inclusion of BSF did not affect PER, but tended to decrease protein digestibility. Several sub-data sets also showed that the use of BSF decreased protein digestibility in salmonids compared to control diets, indicating negative effects of BSF on protein digestibility. The data sets consisted of different variables that can influence these results. In a review, English et al.[16] showed that the rearing substrate of BSF can be responsible for the inconsistency of nutrient digestibility of salmonids fed BSF between the studies. Moreover, similar to other animal protein sources such as fishmeal,[44] the drying method and temperature may have a large impact on the nutritional quality and protein digestibility of insect meals.[45] These influencing factors were not considered in the present study, and the comparison across the studies is thus complicated.

The exoskeleton of insects characteristically contains chitin.[46] The chitin content of the BSF ingredients in the present data set ranged from 3% to 17% (Table S4), and dietary chitin levels varied from 0.2% to 3% (dry matter basis) (Table S3). As previous studies suggested,[11,47,48] chitin can be the reason for observed negative effects (at least tend to) of BSF on growth performance and protein digestibility in several data sets in the present study. The dietary protein contents in the data set mostly covered the requirement of salmon and rainbow trout,[27] but the protein contents were calculated using the nitrogen-to-protein conversion factor of 6.25. Since BSF contains non-protein N from chitin, Janssen et al.[49] and Belghit et al.[50] have recently suggested that a factor between 4.2 and 5 might be more appropriate for BSF to avoid the overestimation of the protein content. Furthermore, chitin is poorly digestible in salmon and rainbow trout (13–40% and 2–5% respectively)[51,52] and can thus act as a filler in the diet.[48] Poorly digestible chitin can also increase faecal N excretion, and leads to overestimate the protein content in the faeces and underestimate the protein digestibility. This shows the importance of correcting the protein digestibility for chitin excreted as non-protein N with faeces, but none of the studies in the present meta-analysis reported a such correction. In addition, the chitin matrix in the exoskeleton of insects contains bound amino acids.[53] This might reduce the availability of protein in BSF for protease enzymes[29] or the activity of protease enzymes.[13] However, Basto et al.[32] reported that chitin alone cannot explain the lower nutrient digestibility in insect meals. Even though chitin can compromise protein digestibility, several studies reported no effect of the use of BSF meal on protein digestibility in both salmon[12] and rainbow trout.[54] The present regression analysis also showed no relationships between dietary chitin level and growth or nutrient utilization parameters. Nevertheless, this should be viewed with caution because only the data from six studies that reported chitin contents were used for these regression analyses.

In addition to chitin, other factors in the BSF, such as saturated fatty acids or other compounds, can also cause negative effects on fish growth. A previous meta-analysis showed that high saturated fatty acids (>39% of total fatty acids) and increasing level of lauric acid in the diet decreased final body weight of fish fed BSF.[18] Nevertheless, two previous studies showed that dietary inclusion of BSF larvae oil (2.5–12%) did not affect the growth performance of salmon[55] and rainbow trout,[14] although the BSF oil diets in Belghit et al.[55] contained high levels of saturated fatty acids and lauric acid (48–51% and 22–29% of total fatty acids respectively). Lauric acid is also considered as a bioactive compound which can have health beneficial effects in animals,[6] but such effects of BSF lauric acid have not yet been verified in salmonids. Hence, more research is needed to confirm the impact of fatty acid profile of BSF on salmonid performance.

A meta-analysis implies limitations associated with diverse nature of studies, and interpretation of effect sizes obtained in a meta-analysis may be controversial, especially if number of relevant studies are limited.[56] The comparison across studies should ideally consider all biological and dietary factors.[36] Many of the variables that exist across studies were considered in the present study, but unexplained heterogeneity still existed among the studies even after considering these influencing factors. Other factors causing discrepancy among studies might be related to the quality of BSF, rearing substrates of BSF, nutrient composition of BSF, level of anti-nutritive as well as bioactive compounds in BSF, degree of defatting of BSF, drying method of BSF and temperatures, level of protein replaced by BSF, diet formulations, method of digestibility measurement, fish size, rearing conditions and culture systems used in studies. Nevertheless, insufficient data prevented us from including these factors in the present analysis, although they might influence greatly the fish response to BSF. Therefore, this topic should be revisited when more research findings are available to identify the various factors affecting the response of salmonids to BSF in diets, which is important for drawing concrete conclusions and making recommendations.

5 | CONCLUSIONS

In the present meta-analysis, the full data set showed that, on average, the growth rate, feed conversion, feed intake, protein digestibility and utilization in salmonids fed BSF diets did not differ from those fed control diets. Variations in these parameters, however, existed between the studies. The fish species, type of protein source(s) replaced and BSF inclusion level were partially responsible for variation in fish SGR, whereas only the type of replaced protein source(s) and BSF inclusion level were detected as factors explaining the variations in FCR and feed intake respectively. The meta-analyses of the sub-data sets sorted according to the protein source(s) replaced showed that replacement of fishmeal by BSF decreased SGR and feed intake of salmonids whereas the replacement of non-fishmeal sources improved SGR and feed conversion. This stressed the importance of type of replaced protein source(s) when evaluating the nutritional value of BSF for salmonids. Overall, the present meta-analysis showed that BSF is a promising protein source for salmonid feeds, but its effectiveness is mainly dependent on the type of replaced protein source(s).

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CONFLICT OF INTEREST

The authors declare no competing conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

1. Nesic K, Zagon J. Insects – a promising feed and food protein source? *Meat Technol*. 2019;60(1):56-67. https://doi.org/10.18485/meattech.2019.60.1.8
2. van Huis A, Oonincx DGAB. The environmental sustainability of insects as food and feed. A review. *Agron Sustain Dev*. 2017;37:43. https://doi.org/10.1007/s13593-017-0452-8
3. van Huis A. Potential of insects as food and feed in assuring food security. *Annu Rev Entomol*. 2013;58:563-583. https://doi.org/10.1146/annurev-ento-120811-153704
4. Makkar HPS, Tran G, Heuzé V, Ankers P. State-of-the-art on use of insects as animal feed. *Anim Feed Sci Technol*. 2014;197:1-33. https://doi.org/10.1016/j.anifeedsci.2014.07.008
5. Wang Y-S, Shelomi M. Review of black soldier fly (*Hermetia illucens*) as animal feed and human food. *Foods*. 2017;6(10):91. https://doi.org/10.3390/foods6100091
6. Veldkamp T, Dong L, Paul A, Govers C. Bioactive properties of insect products for monogastric animals – a review [published online ahead of print July 01, 2021]. *J Insects Food Feed*. In press. https://doi.org/10.3920/JIFF2021.0031
7. Li Y, Bruni L, Jaramillo-Torres A, Gajardo K, Kortner TM, Krogdahl Å. Differential response of digesta- and mucosa-associated intestinal microbiota to dietary insect meal during the seawater phase of Atlantic salmon. *Anim Microbiome*. 2021;3:8. https://doi.org/10.1186/s42523-020-00071-3
8. Huyben D, Vidaković A, Hallgren SW, Langeland M. High-throughput sequencing of gut microbiota in rainbow trout (*Oncorhynchus mykiss*) fed larval and pre-pupae stages of black soldier fly (*Hermetia illucens*). *Aquaculture*. 2019;500:485-491. https://doi.org/10.1016/j.aquaculture.2018.10.034
9. Elia AC, Capucchio MT, Caldaroni B, et al. Influence of *Hermetia illucens* meal dietary inclusion on the histological traits, gut mucin composition and the oxidative stress biomarkers in rainbow trout (*Oncorhynchus mykiss*). *Aquaculture*. 2018;496:50-57. https://doi.org/10.1016/j.aquaculture.2018.07.009
10. Weththasinghe P, Lagos L, Chortés M, Hansen JØ, Øverland M. Dietary inclusion of black soldier fly (*Hermetia Illucens*) larvae meal and paste improved gut health but had minor effects on skin mucus proteome and immune response in Atlantic Salmon (*Salmo salar*). *Front Immunol*. 2021;12:599530. https://doi.org/10.3389/fimmu.2021.599530
11. Weththasinghe P, Hansen JØ, Nøkland D, Lagos L, Rawski M, Øverland M. Full-fat black soldier fly larvae (*Hermetia illucens*) meal and paste in extruded diets for Atlantic salmon (*Salmo salar*): effect on physical pellet quality, nutrient digestibility, nutrient utilization

and growth performances. *Aquaculture*. 2021;530:735785. https://doi.org/10.1016/j.aquaculture.2020.735785

12. Fisher HJ, Collins SA, Hanson C, Mason B, Colombo SM, Anderson DM. Black soldier fly larvae meal as a protein source in low fish meal diets for Atlantic salmon (*Salmo salar*). *Aquaculture*. 2020;521:734978. https://doi.org/10.1016/j.aquaculture.2020.734978
13. Belghit I, Liland NS, Waagbø R, et al. Potential of insect-based diets for Atlantic salmon (*Salmo salar*). *Aquaculture*. 2018;491:72-81. https://doi.org/10.1016/j.aquaculture.2018.03.016
14. Dumas A, Raggi T, Barkhouse J, Lewis E, Weltzien E. The oil fraction and partially defatted meal of black soldier fly larvae (*Hermetia illucens*) affect differently growth performance, feed efficiency, nutrient deposition, blood glucose and lipid digestibility of rainbow trout (*Oncorhynchus mykiss*). *Aquaculture*. 2018;492:24-34. https://doi.org/10.1016/j.aquaculture.2018.03.038
15. Randazzo B, Zarantoniello M, Gioacchini G, et al. Physiological response of rainbow trout (*Oncorhynchus mykiss*) to graded levels of *Hermetia illucens* or poultry by-product meals as single or combined substitute ingredients to dietary plant proteins. *Aquaculture*. 2021;538:736550. https://doi.org/10.1016/j.aquaculture.2021.736550
16. English G, Wanger G, Colombo SM. A review of advancements in black soldier fly (*Hermetia illucens*) production for dietary inclusion in salmonid feeds. *J Agric Food Res*. 2021;5:100164. https://doi.org/10.1016/j.jafr.2021.100164
17. Hua K. A meta-analysis of the effects of replacing fish meals with insect meals on growth performance of fish. *Aquaculture*. 2021;530:735732. https://doi.org/10.1016/j.aquaculture.2020.735732
18. Liland NS, Araujo P, Xu XX, et al. A meta-analysis on the nutritional value of insects in aquafeeds. *J Insects Food Feed*. 2021;7(5):743-759. https://doi.org/10.3920/JIFF2020.0147
19. Papuc T, Boaru A, Ladosi D, Struti D, Georgescu B. Potential of black soldier fly (*Hermetia illucens*) as alternative protein source in salmonid feeds - a review. *Indian J Fish*. 2020;67(4):160-170. https://doi.org/10.21077/ijf.2020.67.4.100172-20
20. Higgins JPT, Thomas J, Chandler J, et al. *Cochrane handbook for systematic reviews of interventions*, 2nd ed. John Wiley & Sons; 2019.
21. Moher D, Liberati A, Tetzlaff J, Altman DG, Group TP. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *PLoS Medicine*. 2009;6(7):e1000097. https://doi.org/10.1371/journal.pmed.1000097
22. Ma J, Liu W, Hunter A, Zhang W. Performing meta-analysis with incomplete statistical information in clinical trials. *BMC Med Res Methodol*. 2008;8:56. https://doi.org/10.1186/1471-2288-8-56
23. Sales J. Effects of *Saccharomyces cerevisiae* supplementation on ruminal parameters, nutrient digestibility and growth in sheep: a meta-analysis. *Small Rumin Res*. 2011;100(1):19-29. https://doi.org/10.1016/j.smallrumres.2011.05.012
24. Borenstein MI, Hedges LV, Higgins JPT, Rothstein HR. *Introduction to meta-analysis*. John Wiley & Sons; 2009.
25. Higgins JPT, Thompson SG. Quantifying heterogeneity in a meta-analysis. *Stat Med*. 2002;21(11):1539-1558. https://doi.org/10.1002/sim.1186
26. Ioannidis JPA, Trikalinos TA. The appropriateness of asymmetry tests for publication bias in meta-analyses: a large survey. *Can Med Assoc J*. 2007;176(8):1091-1096. https://doi.org/10.1503/cmaj.060410
27. NRC. *Nutrient requirements of fish and shrimp*. The National Academies Press; 2011.
28. Renna M, Schiavone A, Gai F, et al. Evaluation of the suitability of a partially defatted black soldier fly (*Hermetia illucens* L.) larvae meal as ingredient for rainbow trout (*Oncorhynchus mykiss* Walbaum) diets. *J Anim Sci Biotechnol*. 2017;8:57. https://doi.org/10.1186/s40104-017-0191-3
29. Henry M, Gasco L, Piccolo G, Fountoulaki E. Review on the use of insects in the diet of farmed fish: past and future. *Anim Feed Sci Technol*. 2015;203:1-22. https://doi.org/10.1016/j.anifeedsci.2015.03.001
30. Nogales-Mérida S, Gobbi P, Józefiak D, et al. Insect meals in fish nutrition. *Rev Aquac*. 2019;11(4):1080-1103. https://doi.org/10.1111/raq.12281
31. Lock ER, Arsiwalla T, Waagbø R. Insect larvae meal as an alternative source of nutrients in the diet of Atlantic salmon (*Salmo salar*) postsmolt. *Aquac Nutr*. 2016;22(6):1202-1213. 10.1111/anu.12343
32. Basto A, Matos E, Valente LMP. Nutritional value of different insect larvae meals as protein sources for European sea bass (*Dicentrarchus labrax*) juveniles. *Aquaculture*. 2020;521:735085. https://doi.org/10.1016/j.aquaculture.2020.735085
33. Shi Z, Li X-Q, Chowdhury MAK, Chen J-N, Leng X-J. Effects of protease supplementation in low fish meal pelleted and extruded diets on growth, nutrient retention and digestibility of gibel carp, *Carassius auratus gibelio*. *Aquaculture*. 2016;460:37-44. https://doi.org/10.1016/j.aquaculture.2016.03.049
34. Ma F, Li X, Li B, Leng X. Effects of extruded and pelleted diets with differing protein levels on growth and nutrient retention of tilapia, *Oreochromis niloticus*× *O. aureus*. *Aquac Int*. 2015;23(6):1341-1356. https://doi.org/10.1007/s10499-015-9888-5
35. Li X-Q, Xu H-B, Sun W-T, Xu X-Y, Xu Z, Leng X-J. Grass carp fed a fishmeal-free extruded diet showed higher weight gain and nutrient utilization than those fed a pelleted diet at various feeding rates. *Aquaculture*. 2018;493:283-288. https://doi.org/10.1016/j.aquaculture.2018.04.058
36. Hua K, Bureau DP. Exploring the possibility of quantifying the effects of plant protein ingredients in fish feeds using meta-analysis and nutritional model simulation-based approaches. *Aquaculture*. 2012;356–357:284-301. https://doi.org/10.1016/j.aquaculture.2012.05.003
37. St-Hilaire S, Sheppard C, Tomberlin JK, et al. Fly prepupae as a feedstuff for rainbow trout, *Oncorhynchus mykiss*. *J World Aquac Soc*. 2007;38(1):59-67. https://doi.org/10.1111/j.1749-7345.2006.00073.x
38. Shomorin GO, Storebakken T, Kraugerud OF, Øverland M, Hansen BR, Hansen JØ. Evaluation of wedge wire screen as a new tool for faeces collection in digestibility assessment in fish: the impact of nutrient leaching on apparent digestibility of nitrogen, carbon and sulphur from fishmeal, soybean meal and rapeseed meal-based diets in rainbow trout (*Oncorhynchus mykiss*). *Aquaculture*. 2019;504:81-87. https://doi.org/10.1016/j.aquaculture.2019.01.051
39. Aksnes A, Hope B, Jönsson E, Björnsson BT, Albrektsen S. Size-fractionated fish hydrolysate as feed ingredient for rainbow trout (*Oncorhynchus mykiss*) fed high plant protein diets. I: growth, growth regulation and feed utilization. *Aquaculture*. 2006;261(1):305-317. https://doi.org/10.1016/j.aquaculture.2006.07.025
40. Gaylord TG, Teague AM, Barrows FT. Taurine supplementation of all-plant protein diets for rainbow trout (*Oncorhynchus mykiss*). *J World Aquac Soc*. 2006;37(4):509-517. https://doi.org/10.1111/j.1749-7345.2006.00064.x
41. Li P, Mai K, Trushenski J, Wu G. New developments in fish amino acid nutrition: towards functional and environmentally oriented aquafeeds. *Amino Acids*. 2009;37:43-53. https://doi.org/10.1007/s00726-008-0171-1
42. Collins SA, Øverland M, Skrede A, Drew MD. Effect of plant protein sources on growth rate in salmonids: meta-analysis of dietary inclusion of soybean, pea and canola/rapeseed meals and protein concentrates. *Aquaculture*. 2013;400–401:85-100. https://doi.org/10.1016/j.aquaculture.2013.03.006
43. Sealey WM, Gaylord TG, Barrows FT, et al. Sensory analysis of rainbow trout, *Oncorhynchus mykiss*, fed enriched black soldier fly prepupae, *Hermetia illucens*. *J World Aquac Soc*. 2011;42(1):34-45. https://doi.org/10.1111/j.1749-7345.2010.00441.x
44. Opstvedt J, Nygård E, Samuelsen TA, Venturini G, Luzzana U, Mundheim H. Effect on protein digestibility of different

processing conditions in the production of fish meal and fish feed. *J Sci Food Agric*. 2003;83(8):775-782. https://doi.org/10.1002/jsfa.1396

45. Oonincx DGAB, Finke MD. Nutritional value of insects and ways to manipulate their composition. *J Insects Food Feed*. 2020;7(5):639-659. https://doi.org/10.3920/JIFF2020.0050
46. Chapman RF. *The insects: Structure and function* (4th ed.). Cambridge University Press; 1998.
47. Hansen JØ, Penn M, Øverland M, et al. High inclusion of partially deshelled and whole krill meals in diets for Atlantic salmon (*Salmo salar*). *Aquaculture*. 2010;310(1–2):164-172. https://doi.org/10.1016/j.aquaculture.2010.10.003
48. Karlsen Ø, Amlund H, Berg A, Olsen RE. The effect of dietary chitin on growth and nutrient digestibility in farmed Atlantic cod, Atlantic salmon and Atlantic halibut. *Aquac Res*. 2017;48(1):123-133. https://doi.org/10.1111/are.12867
49. Janssen RH, Vincken J-P, van den Broek LAM, Fogliano V, Lakemond CMM. Nitrogen-to-protein conversion factors for three edible insects: *Tenebrio molitor*, *Alphitobius diaperinus*, and *Hermetia illucens*. *J Agric Food Chem*. 2017;65(11):2275-2278. https://doi.org/10.1021/acs.jafc.7b00471
50. Belghit I, Lock E-J, Fumière O, et al. Species-specific discrimination of insect meals for aquafeeds by direct comparison of tandem mass spectra. *Animals*. 2019;9(5):222. https://doi.org/10.3390/ani9050222
51. Olsen RE, Suontama J, Langmyhr E, et al. The replacement of fish meal with Antarctic krill, *Euphausia superba* in diets for Atlantic salmon, *Salmo salar*. *Aquac Nutr*. 2006;12(4):280-290. https://doi.org/10.1111/j.1365-2095.2006.00400.x
52. Lindsay GJH, Walton MJ, Adron JW, Fletcher TC, Cho CY, Cowey CB. The growth of rainbow trout (*Salmo gairdneri*) given diets containing chitin and its relationship to chitinolytic enzymes and chitin digestibility. *Aquaculture*. 1984;37(4):315-334. https://doi.org/10.1016/0044-8486(84)90297-7
53. Finke MD. Estimate of chitin in raw whole insects. *Zoo Biol*. 2007;26(2):105-115. https://doi.org/10.1002/zoo.20123
54. Melenchón F, Larrán AM, de Mercado E, et al. Potential use of black soldier fly (*Hermetia illucens*) and mealworm (*Tenebrio molitor*) insectmeals in diets for rainbow trout (*Oncorhynchus mykiss*). *Aquac Nutr*. 2021;27(2):491-505. https://doi.org/10.1111/anu.13201
55. Belghit I, Waagbø R, Lock EJ, Liland NS. Insect-based diets high in lauric acid reduce liver lipids in freshwater Atlantic salmon. *Aquac Nutr*. 2019;25(2):343-357. https://doi.org/10.1111/anu.12860
56. Hansen JØ, Øverland M, Skrede A, Anderson DM, Collins SA. A meta-analysis of the effects of dietary canola/double low rapeseed meal on growth performance of weanling and growing-finishing pigs. *Anim Feed Sci Technol*. 2020;259:114302. https://doi.org/10.1016/j.anifeedsci.2019.114302
57. Liland NS, Biancarosa I, Araujo P, et al. Modulation of nutrient composition of black soldier fly (*Hermetia illucens*) larvae by feeding seaweed-enriched media. *PLoS One*. 2017;12(8):e0183188. https://doi.org/10.1371/journal.pone.0183188
58. Meneguz M, Schiavone A, Gai F, et al. Effect of rearing substrate on growth performance, waste reduction efficiency and chemical composition of black soldier fly (*Hermetia illucens*) larvae. *J Sci Food Agric*. 2018;98(15):5776-5784. https://doi.org/10.1002/jsfa.9127
59. Oonincx DGAB, van Broekhoven S, van Huis A, van Loon JJA. Feed conversion, survival and development, and composition of four insect species on diets composed of food by-products. *PLoS One*. 2015;10(12):e0144601. https://doi.org/10.1371/journal.pone.0144601
60. Barroso FG, de Haro C, Sánchez-Muros M-J, Venegas E, Martínez-Sánchez A, Pérez-Bañón C. The potential of various insect species for use as food for fish. *Aquaculture*. 2014;422–423:193-201. https://doi.org/10.1016/j.aquaculture.2013.12.024
61. Diener S, Zurbrügg C, Tockner K. Conversion of organic material by black soldier fly larvae: establishing optimal feeding rates. *Waste Manag Res*. 2009;27(6):603-610. https://doi.org/10.1177/0734242X09103838
62. Galassi G, Jucker C, Parma P, et al. Impact of agro-industrial byproducts on bioconversion, chemical composition, in vitro digestibility, and microbiota of the black soldier fly (Diptera: Stratiomyidae) larvae. *J Insect Sci*. 2021;21(1):8. https://doi.org/10.1093/jisesa/ieaa148
63. Gold M, Cassar CM, Zurbrügg C, et al. Biowaste treatment with black soldier fly larvae: increasing performance through the formulation of biowastes based on protein and carbohydrates. *Waste Manage*. 2020;102:319-329. https://doi.org/10.1016/j.wasman.2019.10.036
64. Lalander C, Diener S, Zurbrügg C, Vinnerås B. Effects of feedstock on larval development and process efficiency in waste treatment with black soldier fly (*Hermetia illucens*). *J Clean Prod*. 2019;208:211-219. https://doi.org/10.1016/j.jclepro.2018.10.017
65. Smets R, Verbinnen B, Van De Voorde I, Aerts G, Claes J, Van Der Borght M. Sequential extraction and characterisation of lipids, proteins, and chitin from black soldier fly (*Hermetia illucens*) larvae, prepupae, and pupae. *Waste Biomass Valorization*. 2020;11:6455-6466. https://doi.org/10.1007/s12649-019-00924-2
66. Caligiani A, Marseglia A, Leni G, et al. Composition of black soldier fly prepupae and systematic approaches for extraction and fractionation of proteins, lipids and chitin. *Food Res Int*. 2018;105:812-820. https://doi.org/10.1016/j.foodres.2017.12.012
67. Danieli PP, Lussiana C, Gasco L, Amici A, Ronchi B. The effects of diet formulation on the yield, proximate composition, and fatty acid profile of the black soldier fly (*Hermetia illucens* L.) prepupae intended for animal feed. *Animals*. 2019;9(4):178. https://doi.org/10.3390/ani9040178
68. Kuppusamy G, Kong CK, Segaran GC, et al. Hummingbird-leaves-reared black soldier fly prepupae: assessment of nutritional and heavy metal compositions. *Biology*. 2020;9(9):274. https://doi.org/10.3390/biology9090274.
69. Spranghers T, Ottoboni M, Klootwijk C, et al. Nutritional composition of black soldier fly (*Hermetia illucens*) prepupae reared on different organic waste substrates. *J Sci Food Agric*. 2017;97(8):2594-2600. https://doi.org/10.1002/jsfa.8081
70. Abdel-Tawwab M, Khalil RH, Metwally AA, Shakweer MS, Khallaf MA, Abdel-Latif HMR. Effects of black soldier fly (*Hermetia illucens* L.) larvae meal on growth performance, organs-somatic indices, body composition, and hemato-biochemical variables of European sea bass, *Dicentrarchus labrax*. *Aquaculture*. 2020;522:735136. https://doi.org/10.1016/j.aquaculture.2020.735136
71. Belghit I, Liland NS, Gjesdal P, et al. Black soldier fly larvae meal can replace fish meal in diets of sea-water phase Atlantic salmon (*Salmo salar*). *Aquaculture*. 2019;503:609-619. https://doi.org/10.1016/j.aquaculture.2018.12.032
72. Cummins VC Jr, Rawles SD, Thompson KR, et al. Evaluation of black soldier fly (*Hermetia illucens*) larvae meal as partial or total replacement of marine fish meal in practical diets for Pacific white shrimp (*Litopenaeus vannamei*). *Aquaculture*. 2017;473:337-344. https://doi.org/10.1016/j.aquaculture.2017.02.022
73. De Marco M, Martínez S, Hernandez F, et al. Nutritional value of two insect larval meals (*Tenebrio molitor* and *Hermetia illucens*) for broiler chickens: apparent nutrient digestibility, apparent ileal amino acid digestibility and apparent metabolizable energy. *Anim Feed Sci Technol*. 2015;209:211-218. https://doi.org/10.1016/j.anifeedsci.2015.08.006
74. Devic E, Leschen W, Murray F, Little DC. Growth performance, feed utilization and body composition of advanced nursing Nile tilapia (*Oreochromis niloticus*) fed diets containing black soldier fly (*Hermetia illucens*) larvae meal. *Aquac Nutr*. 2018;24(1):416-423. https://doi.org/10.1111/anu.12573

75. Dietz C, Liebert F. Does graded substitution of soy protein concentrate by an insect meal respond on growth and N-utilization in Nile tilapia (*Oreochromis niloticus*)? *Aquac Rep*. 2018;12:43-48. https://doi.org/10.1016/j.aqrep.2018.09.001
76. Finke MD. Complete nutrient content of four species of feeder insects. *Zoo Biol*. 2013;32(1):27-36. https://doi.org/10.1002/zoo.21012
77. Guerreiro I, Serra CR, Coutinho F, et al. Digestive enzyme activity and nutrient digestibility in meagre (*Argyrosomus regius*) fed increasing levels of black soldier fly meal (*Hermetia illucens*). *Aquac Nutr*. 2021;27(1):142-152. https://doi.org/10.1111/anu.13172
78. Rawski M, Mazurkiewicz J, Kierończyk B, Józefiak D. Black soldier fly full-fat larvae meal as an alternative to fish meal and fish oil in siberian sturgeon nutrition: the effects on physical properties of the feed, animal growth performance, and feed acceptance and utilization. *Animals*. 2020;10(11):2119. https://doi.org/10.3390/ani10112119
79. Stejskal V, Tran HQ, Prokesova M, et al. Partially defatted *Hermetia illucens* larva meal in diet of Eurasian perch (*Perca fluviatilis*) juveniles. *Animals*. 2020;10(10):1876. https://doi.org/10.3390/ani10101876
80. Veldkamp T, Bosch G. Insects: a protein-rich feed ingredient in pig and poultry diets. *Anim Front*. 2015;5(2):45-50. https://doi.org/10.2527/af.2015-0019
81. Józefiak A, Nogales-Mérida S, Mikołajczak Z, Rawski M, Kierończyk B, Mazurkiewicz J. The utilization of full-fat insect meal in rainbow trout (*Oncorhynchus mykiss*) nutrition: the effects on growth performance, intestinal microbiota and gastrointestinal tract histomorphology. *Ann Anim Sci*. 2019;19(3):747-765. https://doi.org/10.2478/aoas-2019-0020
82. Magalhães R, Sánchez-López A, Leal RS, Martínez-Llorens S, Oliva-Teles A, Peres H. Black soldier fly (*Hermetia illucens*) pre-pupae meal as a fish meal replacement in diets for European seabass (*Dicentrarchus labrax*). *Aquaculture*. 2017;476:79-85. https://doi.org/10.1016/j.aquaculture.2017.04.021
83. Barroso FG, Sánchez-Muros M-J, Segura M, et al. Insects as food: Enrichment of larvae of *Hermetia illucens* with omega 3 fatty acids by means of dietary modifications. *J Food Compost Anal*. 2017;62:8-13. https://doi.org/10.1016/j.jfca.2017.04.008
84. Cullere M, Woods MJ, van Emmenes L, Pieterse E, Hoffman LC, Dalle ZA. *Hermetia illucens* larvae reared on different substrates in broiler quail diets: effect on physicochemical and sensory quality of the quail meat. *Animals*. 2019;9(8):525. https://doi.org/10.3390/ani9080525
85. Ewald N, Vidakovic A, Langeland M, Kiessling A, Sampels S, Lalander C. Fatty acid composition of black soldier fly larvae (*Hermetia illucens*) – possibilities and limitations for modification through diet. *Waste Manage*. 2020;102:40-47. https://doi.org/10.1016/j.wasman.2019.10.014
86. Fischer H, Romano N, Sinha AK. Conversion of spent coffee and donuts by black soldier fly (*Hermetia illucens*) larvae into potential resources for animal and plant farming. *Insects*. 2021;12(4):332. https://doi.org/10.3390/insects12040332
87. Kierończyk B, Sypniewski J, Rawski M, Czekała W, Świątkiewicz S, Józefiak D. From waste to sustainable feed material: the effect of *Hermetia illucens* oil on the growth performance, nutrient digestibility, and gastrointestinal tract morphometry of broiler chickens. *Ann Anim Sci*. 2020;20(1):157-177. https://doi.org/10.2478/aoas-2019-0066
88. Reyes M, Rodríguez M, Montes J, et al. Nutritional and growth effect of insect meal inclusion on seabass (*Dicentrarchuss labrax*) feeds. *Fishes*. 2020;5(2):16. https://doi.org/10.3390/fishes5020016
89. Romano N, Fischer H, Kumar V, Francis SA, Sinha AK. Productivity, conversion ability, and biochemical composition of black soldier fly (*Hermetia illucens*) larvae fed with sweet potato, spent coffee or dough. *Int J Trop Insect Sci*. [published online on 11 April 2021]. https://doi.org/10.1007/s42690-021-00532-5
90. Marco AE, Ramzy RR, Ji H. Influence of substrate inclusion of quail manure on the growth performance, body composition, fatty acid and amino acid profiles of black soldier fly larvae (*Hermetia illucens*). *Sci Total Environ*. 2021;772:145528. https://doi.org/10.1016/j.scitotenv.2021.145528
91. Marco AE, Ramzy RR, Plath M, Ji H. Evaluating the impact of bird manure vs. mammal manure on *Hermetia illucens* larvae. *J Clean Prod*. 2021;278:123570. https://doi.org/10.1016/j.jclepro.2020.123570
92. Marco AE, Ramzy RR, Wang D, Ji H. Sustainable management of Se-rich silkworm residuals by black soldier flies larvae to produce a high nutritional value and accumulate ω-3 PUFA. *Waste Manage*. 2021;124:72-81. https://doi.org/10.1016/j.wasman.2021.01.040.
93. Moutinho S, Pedrosa R, Magalhães R, Oliva-Teles A, Parisi G, Peres H. Black soldier fly (*Hermetia illucens*) pre-pupae larvae meal in diets for European seabass (*Dicentrarchus labrax*) juveniles: effects on liver oxidative status and fillet quality traits during shelf-life. *Aquaculture*. 2021;533:736080. https://doi.org/10.1016/j.aquaculture.2020.736080
94. Roques S, Deborde C, Guimas L, et al. Integrative metabolomics for assessing the effect of insect (*Hermetia illucens*) protein extract on rainbow trout metabolism. *Metabolites*. 2020;10(3):83. https://doi.org/10.3390/metabo10030083
95. Cardinaletti G, Randazzo B, Messina M, et al. Effects of graded dietary inclusion level of full-fat *Hermetia illucens* prepupae meal in practical diets for rainbow trout (*Oncorhynchus mykiss*). *Animals*. 2019;9(5):251. https://doi.org/10.3390/ani9050251
96. Terova G, Rimoldi S, Ascione C, Gini E, Ceccotti C, Gasco L. Rainbow trout (*Oncorhynchus mykiss*) gut microbiota is modulated by insect meal from *Hermetia illucens* prepupae in the diet. *Rev Fish Biol Fish*. 2019;29:465-486. https://doi.org/10.1007/s11160-019-09558-y
97. Stadtlander T, Stamer A, Buser A, Wohlfahrt J, Leiber F, Sandrock C. *Hermetia illucens* meal as fish meal replacement for rainbow trout on farm. *J Insects Food Feed*. 2017;3(3):165-175. https://doi.org/10.3920/JIFF2016.0056

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