Canrea Journal: Food Technology, Nutritions, and Culinary, 2024; 7 (1): 66-78

OPEN ACCESS

e-ISSN : 2621-9468

Type of the Paper (Review Article)

Effect of different feed on nutritional content of black soldier fly (*Hermetia illucens*): A systematic review and meta-analysis

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Abstract

Black Soldier Fly (*Hermetia illucens*) or BSF is commonly used in food industry as a meat substitute to reduce food waste and environmental pollution. It could grow effectively using organic material such as manure and food waste. In this study, a comparison of the nutritional content of BSF fed with manure and food waste will be determined by conducting a systematic review and meta-analysis. The information about protein, fat, carbohydrate, ash, and calcium content of manure or food waste fed BSF from various scientific database sources was analyzed and discussed. There were 720 literatures selected to be included in the meta-analysis dataset, with the main selection criteria: original research articles published in the last ten years with nutritional data on manure and food waste fed BSF. From the literature screening process, 8 articles were obtained and included in the meta-analysis. Based on meta-analysis, it was found that the food waste fed BSF group has approximately 16% higher protein content, 33% higher fat content, but 59% lower ash content if compared to manure fed BSF group. However, the use of food waste as BSF feed did not give a significant effect on BSF carbohydrate and calcium content when compared to manure fed BSF.

Article History
Received October, 19 2023
Accepted June, 15 2024
Published June, 24 2024

Keywords
Black Soldier Fly, Manure, Food Waste, Nutrition Content, Edible Insect.

1. Introduction

The industrial agricultural system has been identified as a significant source of environmental pollution through factory farming (1), as well as one of the main generators of greenhouse gas emissions through food waste (2). As estimated one third of food produced for global human consumption is lost and wasted annually (3). The buildup of food waste can promote environmental pollution, one of which is induced by the emission of harmful gases that can cause the greenhouse effect. Each kilogram of waste can produce 0.5 m^3 of methane gas which contributes as much as 15% of global warming (4). In addition, factory farming such as ruminant and chicken farming is also one of the largest contributors of methane gas accounts for 12-41% (5). The impact of the presence of methane gas in the atmosphere is air

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ISSN 2621-9468 online, DOI 10.20956/canrea.v7i1.1153

pollution, global climate change, depletion of the atmosphere ozone layer, and acid rain. Methane gas can also cause an explosion at the landfill if its concentration reaches 5-15% in air.

Studies show BSF larvae can break down a significant amount of organic waste. For instance, BSF larvae effectively reducing up to 62,6% food waste (6). Maggot BSF can digest organic waste by reducing organic waste by 65.5% to 78.9% per day from the amount of food it gets (7).

World meat consumption has quadrupled since 1961 in absolute and per capita terms where approximately 80 billion animals are slaughtered annually to produce 340 million tons of meat for human consumption (8). The increase in meat consumption which requires livestock activities and the emerging food waste issues along with the increase in human population can cause negative impacts on the environment. Climate change and environmental deterioration inspire people to reduce meat consumption and aiming for alternative protein consumption (9). Therefore, the use of insects such as black soldier fly (BSF) as a decomposer of organic waste and as an alternative protein source is expected to be one of the solutions that can contribute to reducing food waste and livestock activities (10).

Black soldier fly (BSF) is a type of fly from the *Stratiomyidae* family that could be used in food industry such as for meat substitute (11), production of fat-based margarine (12), and flour utilization (13). BSF larvae are a fairly efficient source of protein and fat ranging from 40% and 30% (14), respectively and can be processed into flour with a protein content of 32-58% (15). When BSF larvae are in the pre-pupa stage, they will naturally leave the substrate and move to a high and clean place, this behavior is called “self-harvesting” which greatly assist workers in harvesting BSF larvae (16).

BSF can thrive effectively on organic matter such as food waste, manure, grains, fruits and vegetables, rice straw, etc. Manure is an example of a very common organic material used as feed for BSF. However, manure buildup can cause environmental pollution, increased nitrate in the soil, and result in the contamination of harmful bacteria (17). Therefore, the use of a cleaner and less hazardous source of BSF feed such as food waste might be crucial in yielding BSF for consumption. The diversity of organic waste substrates that can be decomposed by BSF and their decomposition efficiency has the highest value among other types of flies (18). BSF ability to decompose organic matter is related to the bacteria and enzyme found in the digestive tract of the larvae, where the decomposition products are nutrients such as fat and protein (19). There are several benefits of composting food waste using BSF, such as treating organic waste effectively, while also reducing bacterial growth and unpleasant odors (20). In addition, waste treatment using BSF is easy to operate and does not require a large area.

BSF feed comes from the decomposed organic matter itself and therefore, giving different types of feed can greatly affect the nutritional value and the development and growth of BSF (21). BSF ability to decompose organic waste is effective and its potential as an alternative protein source is expected to be one of the solutions to the accumulated urban waste issue, especially in decomposing food waste while also turning food waste to a sustainable food source. Therefore, in this study, a comparison of the nutritional content of BSF fed with manure and food waste will be analyzed by conducting systematic review and meta-analysis to determine whether the application of food waste as feed to BSF can produce

BSF with a higher nutritional value. The articles included are those that directly give and compare two BSF feed treatments, such as manure as control and food waste as experiment.

2. Methods

Data collected in June-October 2022. Literature search was conducted through scientific databases, such as Scopus, ScienceDirect, Proquest, and Google Scholar. The are several keywords used in the literature search, i. e. 'manure' 'food waste' 'substrate' 'effect' 'black soldier fly' 'nutrition'. The search strategy was conducted manually. These initial searches resulted in 720 potential references. There were several criteria used for the literature selection: (1) articles must be published between 2012-2022; (2) original research article (not reviews, meta-analysis, etc.); and (3) direct comparison made between manure fed and food waste fed BSF on BSF nutritional content. The meta-analysis in this study complied to the principle of preferred reporting items for systematic reviews and meta-analysis (PRISMA) (22). The flow diagram for the selection of studies to be included in the meta-analysis dataset this study is shown as Figure 1.

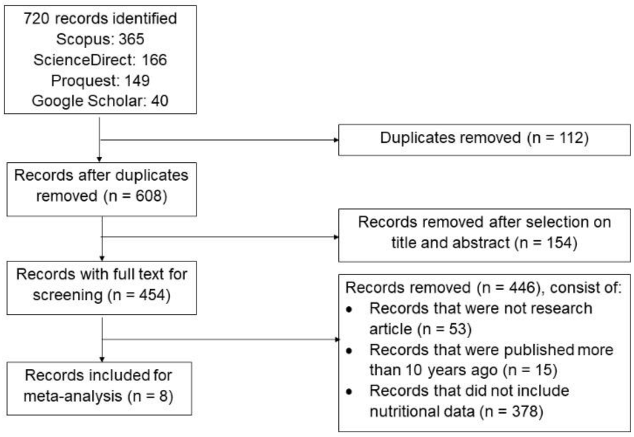

Figure 1. The preferred reporting items for systematic reviews and meta-analysis (PRISMA) flow chart of the literature review process.

From the screening process, a total of 8 records were used to be included in the dataset of meta-analysis and 712 records were eliminated for various reasons, such as duplicates (112 records), irrelevant topic and or journal title/abstract with no full text available (154 records), records that were not original research article (53 records), records that were published outside of the scope of the time period (2012-2022) (15 records), and records that did not include detailed nutritional data of BSF (378 records).

Several description variables were used as shown in Table 1 to elaborate information about the articles included in this study. These variables included study place, object observed, sample size of the manure fed BSF and food waste fed BSF groups, and references. The mean value and standard deviation of several parameters were recorded and tabulated for further data analysis. These parameters are protein content (Table 2), fat content (Table 3), carbohydrate content (Table 4), ash content (Table 5), and calcium (Table 6). Minerals other than calcium were excluded from the parameters due to lack of available information, because the number of studies (one) was too small to quantify. A minimum of two studies are required to measure the cumulative effect in this study. The effect size (Hedges' d) was determined to quantify the parameter distance between the manure (abbreviated as m) fed BSF and food waste (abbreviated as fw) fed BSF. The effect size (d) was defined as:

$$d= \frac{(X_{fw} - X_m)}{S} \times J, \tag{1}$$

where X_{fw} is the mean value from food waste fed BSF nutrition parameter and X_m is the mean value from manure fed BSF nutrition parameter. J is the correction factor for small sample size, that is defined as:

$$J=1- \frac{3}{(4 (N_m + N_{fw} -2)-1)}, \tag{2}$$

while S is the pooled standard deviation, that is defined as:

$$S= \frac{(N_{fw}-1)(S_{fw})^2 + (N_m-1)(S_m)^2}{(N_{fw} + N_m -2)}, \tag{3}$$

where N_{fw} is the sample size from food waste fed BSF group and N_m is the sample size from manure fed BSF. S_{fw} is the standard deviation of food waste fed BSF group and S_m is the standard deviation of manure fed BSF group. The variance of Hedges' d is defined as:

$$V_d = \frac{(N_m + N_{fw})}{N_m N_{fw}} + \frac{d^2}{(2 (N_m + N_{fw}))}, \tag{4}$$

while cumulative effect size is defined as:

$$d_{++} = \frac{(\sum_{i=1}^{n} \frac{1}{V_d} \times d)}{\frac{1}{Vd}}. \tag{5}$$

Table 1. List of studies included in meta-analysis.

Study Code	Place	Animal	Nm	Nfw	References
1	India	BSF larvae	3	3	(23)
2	Kenya	BSF larvae	2	2	(24)
3	Switzerland	BSF larvae	3	3	(25)
4	US	BSF larvae	5	5	(26)
5	Switzerland	BSF larvae	3	3	(27)
6	Kenya	BSF larvae	3	3	(16)
7	China	BSF prepupae	3	3	(28)
8	Belgium	BSF prepupae	2	2	(29)

N_m, sample size from manure feed BSF studies; N_{fw}, sample size from food waste feed BSF studies.

Table 2. The mean value, standard deviation, and replications of protein parameter.

Journal	Manure Fed BSF			Food Waste Fed BSF		
	Mean	Standard Deviation	n	Mean	Standard Deviation	n
1	30.17%	0.05	3	49.24%	0.15	3
2	30.17%	0.5	2	33.00%	1	2
3	36.20%	0.2	3	36.10%	0.3	3
4	45.94%	0.48	5	49.89%	0.21	5
5	11.10%	0.05	3	32.20%	0.8	3
6	45.40%	0.1	3	43.00%	1	3
7	42.83%	4.36	3	43.69%	4.29	3
8	41.20%	0.06	2	43.10%	0.06	2

Table 3. The mean value, standard deviation, and replications of fat parameter.

Journal	Manure Fed BSF			Food Waste Fed BSF		
	Mean	Standard Deviation	n	Mean	Standard Deviation	n
1	11.39%	0.06	3	19.19%	0.05	3
4	17.53%	0.4	5	33.71%	0.31	5
6	18.10%	0.3	3	27.20%	1	3
7	36.52%	3.92	3	37.24%	3.27	3
8	33.60%	0.04	2	38.60%	0.23	2

Table 4. The mean value, standard deviation, and replications of carbohydrate parameter.

Journal	Manure Fed BSF			Food Waste Fed BSF		
	Mean	Standard Deviation	n	Mean	Standard Deviation	
1	37.76%	0.1	3	37.52%	0.34	1
3	56.10%	0.3	3	52.80%	0.3	3
5	58.40%	0.4	3	36.20%	1.4	5

Table 5. The mean value, standard deviation, and replications of ash parameter.

Journal	Manure Fed BSF			Food Waste Fed BSF		
	Mean	Standard Deviation	n	Mean	Standard Deviation	
1	17.32%	0.09	3	12.48%	0.03	3
4	23.95%	0.24	5	5.72%	0.1	5
7	3.71%	0.36	3	3.08%	0.29	3
8	10.00%	0.1	2	2.70%	0.3	2

Table 6. The mean value, standard deviation, and replications of calcium parameter.

Journal	Manure Fed BSF			Food Waste Fed BSF		
	Mean	Standard Deviation	n	Mean	Standard Deviation	n
1	2.88%	0.14	3	9.47%	0.13	3
2	0.32%	0.24	2	0.17%	0.05	2

All the formulas are adopted from Palupi et al. (30) meta-analysis study in 2012. Effect size precision was determined by utilizing 95% confidence interval. The effect size was significant if the confidence interval did not reach the null effect size. Fail safe number was determined to diagnose publication bias due to inconsequential studies which did not count in the meta-analysis. If the fail-safe number was higher than the total of sample size multiplied by five plus ten, it could be concluded that the model of the meta-analysis is robust. All of the calculations and forest plot were calculated and obtained by using OpenMee open-source software.

3. Results and Discussion

The results of this study were obtained through systematic review and meta-analysis could be seen in Figure 2. It indicated the forest plot of cumulative effect size and 95% confidence interval of protein, fat, carbohydrate, ash, and calcium content comparing manure and food waste fed BSF. It can be concluded that the protein and fat content of food waste fed BSF were significantly higher than that of manure fed BSF at a significance level of 0.05. Meanwhile, the ash content of food waste fed BSF was significantly lower than that of manure fed BSF at a significance level of 0.05. In addition, the carbohydrate content of the food waste fed BSF was not significantly lower than that of the manure fed BSF at a significance level of 0.05, and the calcium content in the food waste fed BSF was not significantly higher than that of the manure fed BSF at a significance level of 0.05.

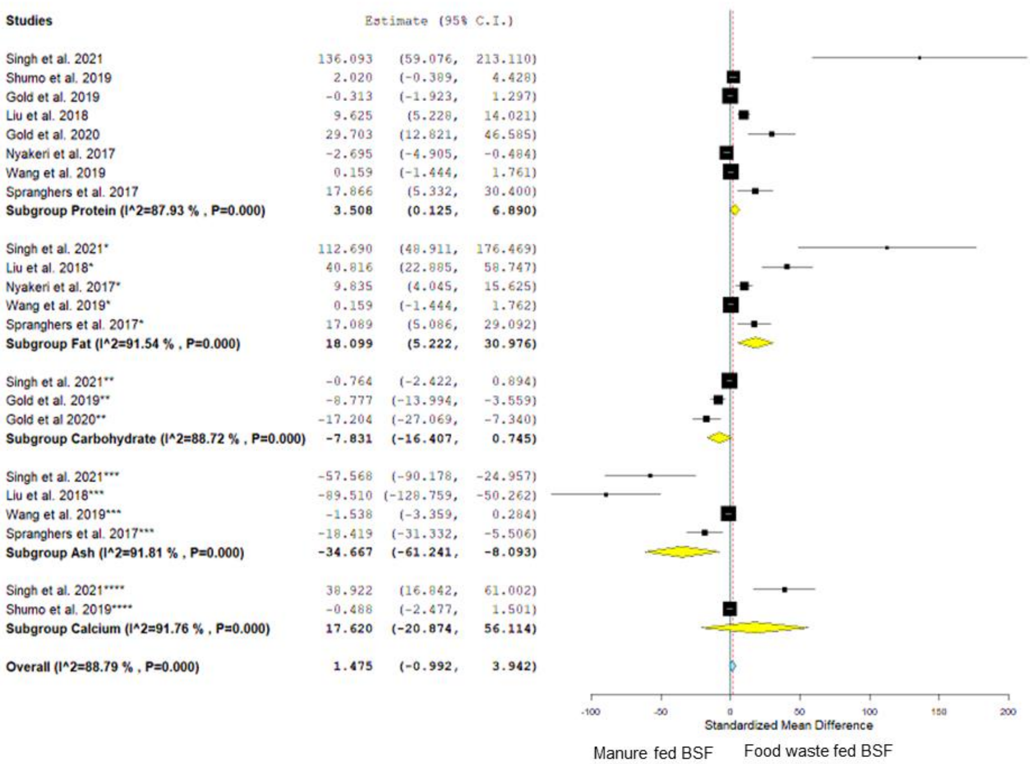

Figure 2. Forest plot of cumulative effect size (d_{++}) and 95% confidence interval (CI) of some nutrition content comparing manure fed and food waste fed BSF.

The research results are elaborated in more detail in Table 7 which showed the cumulative effect size, weighted mean value, and weighted p-value from the nutrition parameters observed. The size effect of protein, fat, and calcium are positive, indicating that the parameters observed was greater than the control group. Meanwhile, the effect size of carbohydrate and ash are negative, indicating that the parameters observed was lower than the control group. The mean value of each parameters observed is provided. From the p-value of each parameters, it could be concluded that comparison of protein, fat, and ash content in food waste and manure fed BSF was significant because the p-value was lower than 0.05 and the CI did not reach the null effect size. Meanwhile, the comparison of data on carbohydrate content and calcium content in food waste and manure fed BSF was not significant because the p-value was greater than 0.05 and the CI reached the null effect size. However, this statement was not robust based on N_{fs} calculation due to high diversity with uncertain range of data or parameter observed from the journals collected in conducting this systematic meta-analysis.

Table 7. The cumulative effect size, weighted mean value, and weighted p-value of all nutrition parameters.

Parameters	Unit	d++	± 95% CI	N	Nfs	Xm	Xfw	SEM	p-value
Protein	%	3.508	3.382	24	56NR	35.38	41.28	1.726	0.042*
Fat	%	18.099	12.877	16	70NR	23.43	31.19	6.57	0.006*
Carbohydrate	%	-7.831	8.576	9	19NR	50.75	42.17	4.376	0.073
Ash	%	-34.667	26.574	13	53NR	13.74	5.60	13.558	0.011*
Calcium	%	17.62	38.494	5	2NR	1.60	4.82	19.64	0.370

*d_{++}, cumulative size effect; CI, confidence interval; N, study size for effect size calculation; N_{fs}, fail-safe number; X_m, weighted mean value from manure fed BSF; X_{fw}, weighted mean value from food waste fed BSF; SEM, standard error of the mean; R, model is robust (N_{fs} > 5N + 10); NR, model is not robust (N_{fs} ≤ 5N + 10). *p-value < 0.05, significant.*

The nutrient content of the substrate or growth media given to BSF will determine the BSF nutrition. The increasing of nutrient quality in the growing media or the substrate given will increase nutrient content in BSF (31). Media or substrate that has high quantity and quality will have a positive impact on the quantity and quality of the BSF nutrients produced. The balance between water content, fat content, protein content, and other nutrients is important for BSF growth and development (32). Nugroho *et al.* (33) show that BSFL which fed fermented Palm Kernel Meal (PKM) has significant carbohydrate and ash content than BSFL which fed fermented cow manure (CM) for 15 days. Carbohydrate content BSFL fermented cow manure higher than BSFL Palm Kernel Meal, orderly 35.45 ± 0.06 % and 33.34 ± 0.04 %. But for the ash (include calcium) BSFL Palm Kernel Meal higher than BSFL fermented cow manure, orderly 13.18 ± 0.04% and 11.14 ± 0.04%.

Based on the systematic meta-analysis result, the protein content and fat content of food waste fed are ranged around 41% and 31% respectively. Other research conducted by Andari et al. (34) reported similar range of protein content and fat content of food waste fed BSF, i.e., around 40% and 25% respectively. In addition, food waste fed BSF had significantly higher protein content and fat content than that of the manure fed BSF (35). The protein and fat content in food waste tended to be higher than manure. Therefore, the utilization of food waste as BSF feed will lead to BSF yield with higher content of protein and fat when compared to BSF fed using manure. Research conducted by Siddiqui et al. (36) also demonstrate that food waste substrate content has a higher protein and fat when compared to the protein content and fat content of the manure substrate. Increasing in fat and protein content on the substrate digested by the BSF led into an increase of fat and protein content in the BSF yield [32].

Furthermore, based on this meta-analysis result, the ash content of manure fed BSF is significantly higher (around 13%) than that of food waste fed BSF (around 5%). This is in accordance with the research results of another study conducted by Julita et al. (37), where the manure fed BSF has higher ash content when compared to food waste fed BSF. Manure is commonly used on agricultural land to improve fertility and soil structure due to the abundance of nitrogen and metallic minerals such as magnesium, potassium, and calcium (38). Manure also contains high mineral content when compared to food waste, hence, the ash content in manure fed BSF is higher than food waste fed BSF (39). A study reported that BSF reared by using manure substrate had noticeably high mineral content, which might be a result of the high mineral content in manure substrate (40). There is another presumption, that is the BSF reared on manure might be absorbing more diet for energy homeostasis as a retribution due to the lack of digestible nutrients in manure substrates, which might have eventually led to an excessive mineral intake (26). Therefore, manure fed BSF has the potential for animal consumption when high mineral intake is required. As for human consumption, manure fed BSF might not be recommended to be consumed due to its rearing substrate hygiene (41).

BSFL differed in terms of nutrient composition depending on the organic substrates they were reared on. Protein, minerals, amino acids, but not vitamins were affected by the different rearing substrates (42). All materials suitable as feeding material for black soldier fly, the difference on physical properties and chemical content affected the development time, harvested biomass, efficiency of digestivity, and efficiency of biomass production which is unique for each type of waste (43).

From the result of this meta-analysis research, it showed that the carbohydrate and calcium content are not significantly different for either manure fed BSF or food waste fed BSF. The highlight of manure nutritional content was it possessed higher overall mineral content when compared to food waste, while food waste substrates tend to have higher protein and fat content with less mineral content (29). In general, BSF tends to prefer to consume food waste, considering that BSF needs a good nutrition intake for its growth, especially high levels of body fat for development from the larval stage to the prepupae stage (44). In general, food waste has the highest fat and protein content compared to other types of waste consumed by BSF. This led to high fat and protein content in the BSF body, especially BSF that consumed food waste in the rearing process (45).

The study might have shown that BSF larvae can partially replace conventional protein sources like fishmeal or soymeal in animal feed. This is a positive finding, suggesting BSF can lessen dependence on traditional methods and potentially reduce pressure on resources like fish stocks or agricultural land. The study found BSF larvae to have high protein content with a good amino acid profile, it strengthens the case for BSF as a viable alternative.

4. Conclusions

The effect of different feed on BSF nutrition was analyzed using systematic and meta-analysis method by assessing 720 articles and results showed that treatment of using food waste to feed BSF had the potential to yield BSF with 16% higher protein content, 33% higher fat content, but 59% lower ash content if compared to manure fed BSF. However, the use of food waste as BSF feed did not give a significant effect on BSF carbohydrate and calcium content if compared to manure fed BSF. It was beneficial in improving the quality of food nutrition, considering that BSF fed with food waste had the potential to be utilized for human or animal consumption when a high intake of protein and fat is required. As for the need for high mineral intake in animals, BSF fed with manure can be utilized and consumed. Based on the results of meta-analysis and to obtain BSF with high protein and fat content, it is recommended to use food waste feed on the rearing process.

Acknowledgement

The authors are grateful to the European Commission through the Erasmus+ CBHE project, for their financial support for this research, project number 618717-EPP-1-2020-1-ID-EPPKA2-CBHE-JP.

Author contributions

D.L. Conceptualization (equal); Writing-review and editing (equal). **L.L.** Investigation (equal); Writing-original draft (equal); Writing-review & editing (equal). **F.A.A.** Supervision (equal); Investigation (equal); Methodology (equal). **A.R.** Data curation (equal); Supervision (equal); Writing-review & editing (equal). **F.T.** Data curation (equal); Supervision (equal); Writing-review & editing (equal). **T.S.** Data curation (equal); Supervision (equal). **E.R.K.** Data curation (equal); Supervision (equal). **A.Z.** Data curation (equal); Supervision (equal). **R.K.C.** Data curation (equal); Supervision (equal).

Funding

This research was co-funded by the European Commission through the Erasmus+ CBHE project "Resolving A Societal Challenge: Interdisciplinary Approach Towards Fostering Collaborative Innovation in Food Waste Management" (IN2FOOD), project number 618717-EPP-1-2020-1-ID-EPPKA2-CBHE-JP. The European Commission's support for the production of this publication does not constitute an endorsement of the contents, which reflect the views only of the authors, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

Institutional Review Board Statement

Not applicable.

Data Availability Statement

Invalid.

Conflicts of Interest

Authors may declare no conflict of interest.

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