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Meta-analysis on the fatty acid composition of edible insects as a sustainable food and feed

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ABSTRACT

Edible insects align with multiple SDGs by offering sustainable solutions for zero hunger, food security, environmental conservation, health and economic development. Further assessment on their benefits might support wider utilization. The current work intended to elucidate the composition of fatty acids from the top 10 most researched edible insects using meta-analysis. A total of 222 articles was chosen and analyzed using a mixed-effects model and Hedges' d effect size. The observed parameters were 25 short- and medium-chain fatty acids, and 17 long-chain fatty acids. Further evaluation of the fatty acids content compared to beef was also performed. Mealworm, Mulberry silkworm, and Long-horned grasshopper were found to contain the highest levels of unsaturated fatty acids (73.4, 68.6 and 63.7 % of total lipids, respectively). The Mulberry silkworm found to have the highest omega-3 content (13.7 % of total lipids). Compared to beef, some edible insects seem promising for providing nutritious fatty acids. Moreover, these favorable content of lauric and myristic acids provide some expected advantages for further utilization as a feed, which produces more nutritious livestock with lower greenhouse gas emissions. Further research is needed to enhance the promotion of locally edible insects as viable sources of nutritious food and feed.

1. Introduction

Edible insects provide a sustainable solution for numerous urgent challenges. They require far fewer resources for farming than traditional livestock, which helps promote environmental sustainability by decreasing the need for land, water, and feed while minimizing greenhouse gas emissions (Orkusz, 2021; van Huis, 2020). Insects efficiently convert feed into edible biomass, making insect farming a highly resource-efficient alternative (Nasir et al., 2024). Additionally,

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Nomenclature

SFA	Saturated Fatty Acid
MUFA	Mono Unsaturated Fatty Acid
PUFA	Poly Unsaturated Fatty Acid
UFA	Unsaturated Fatty Acid
n-3	Omega 3
n-6	Omega 6
EPA	Eicosapentaenoic Acid
DHA	Docosahexaenoic Acid
ARA	Arachidonic Acid
ALA	y-Linoleic acid
C8:0	Caprylic acid
C9:0	Pelargonic acid
C10:0	Capric acid
C11:0	Undecylic acid
C12:0	Lauric acid
C13:0	Tridecylic acid
C14:0	Myristic acid
C14:1	Myristoleic acid
C15:0	Pentadecylic acid
C15:1 (cis-10)	Pentadecanoic acid
C16:0	Palmitic acid
C16:1n-7	Hypogeic acid
C16:1(cis-9)	cis-Palmitoleic acid
C16:1(trans)	trans-Palmitoleic acid
C17:0	Margaric acid
C17:1n-7	Heptadecenoic Acid
C17:1 (cis-10)	cis-Heptadecenoic Acid
C18:0	Stearic acid
C18:1n-9	Oleic acid
C18:1n-11	Vaccenic acid: VA
C18:1(trans)	Elaidic acid
C18:1(*cis*)	Oleic acid
C18:2n-6	Linoleic acid
C18:3n-3	y-Linoleic acid: ALA
C18:3 all-cis-*cis* 6.9.12	y-Linoleic acid
C19:0	Nonadecylic acid
C20:0	Arachidic acid
C20:4(ω−6)	Arachidonic Acid: ARA
C20:5($n-3$)	Eicosapentaenoic Acid: EPA
C21:0	Heneicosylic acid
C22:0	Behenic acid
C22:6($n-3$)	Docosahexaenoic Acid: DHA
C23:0	Tricosylic acid
C24:0	Lignoceric acid

promoting insect consumption helps alleviate pressure on wild fish and game populations, supporting biodiversity conservation (van Huis et al., 2013). Edible insects are also rich in nutrients and offer a sustainable protein source that can address malnutrition and food insecurity, particularly in regions with limited access to nutritious food (Palupi et al., 2020). They are not only rich in protein but also offer essential fatty acids, such as omega-3 and omega-6, which are critical for maintaining cardiovascular and cognitive health (Rumpold and Schlüter, 2013). They also supply key micronutrients, including iron, zinc, and vitamin B12—commonly deficient in many populations—with higher bioavailability, enhancing nutrient absorption and utilization (Finke, 2013). Moreover, insect farming provides economic opportunities for small-scale farmers and promotes cultural acceptance and culinary innovation (Halloran et al., 2016). Integrating edible insects into diets and food systems can greatly contribute to sustainable development across various dimensions. Even some edible insects, such as certain species of Lepidoptera, have been used for medicinal purposes (Yen, 2015).

The previous meta-study on edible insects reached a concrete conclusion by analyzing 222 selected articles from a pool of 10,119, concentrating on the protein and mineral quality of edible insects compared to beef (Nasir et al., 2024). The review showed that despite edible insects having significantly lower protein content compared to beef, some types of edible insects, such as *T. Molitor* (mealworm) and *H. illucens* (BSF), provide higher amino acid scores compared to beef. This indicates that some edible insects have great potential as high-quality proteins for future food. Furthermore, the study demonstrated that edible insects contain significantly higher levels of some minerals such as Ca, Fe, and Zn compared to beef (Nasir et al., 2024).

A reported meta-analysis on concentration of fat demonstrated a cumulative effect size (d_+) 7.02, indicating that edible insects have a significantly higher (p-value$<$0.001) fat content than beef (Nasir et al., 2024). Nevertheless, a further 50 fatty acids have not yet been synthesized and revealed in the previous study. This study intended to further elucidate the composition of fatty acids from edible insects for food and feed through a meta-analysis approach. Considering the fatty acid composition for daily consumption is crucial due to its varied effects on health (Simopoulos, 2002). A balanced fatty acid intake is essential for overall health and disease prevention (Calder, 2015). Omega-3 fatty acids promote heart health by lowering triglyceride levels, reducing inflammation, and minimizing heart disease risk (Mozaffarian and Wu, 2011). Additionally, omega-3 s, particularly EPA and DHA, support brain function, aiding neuronal membrane structure and cognitive health (Freeman et al., 2006). Managing inflammation is vital because the omega-6 to omega-3 ratio influences inflammation levels; excessive omega-6 intake, often from processed vegetable oils, can lead to chronic inflammation (Simopoulos, 2016). Fatty acids also contribute to cell membrane integrity, hormonal balance, and overall health (Stillwell and Wassall, 2003).

This follow-up meta-analysis was also crucial from a feed science perspective because of the growing need for sustainable and efficient protein sources for animal nutrition. Traditional livestock feed resources, such as grains and fishmeal, face challenges, including high environmental impacts, fluctuating prices, and limited availability (Makkar et al., 2014; Liceaga 2021). Edible insects rich in essential fatty acids offer a promising alternative to alleviate these issues. Their low greenhouse gas emissions, high feed conversion efficiency, and minimal land and water requirements make them an environmentally sustainable option (van Huis et al., 2013). Furthermore, understanding the specific fatty acid profiles of edible insects can help optimize their use in enhancing animal health and productivity. Fatty acids are essential for cellular functions, immune responses, and the overall health of livestock (Calder, 2015). By elucidating these profiles, this research can contribute to the formulation of balanced diets that improve livestock performance and reduce reliance on conventional feed resources, thus addressing both economic and environmental concerns (Sogari et al., 2019; Liceaga 2021).

2. Materials and methods

2.1. Article searching, selecting, and data coding

This study was conducted according to Nasir et al. (2024). The literature search across various databases (Scopus, Science Direct, PubMed, Wiley Online Library, JSTOR, MDPI, ScieLo, Taylor & Francis, SagePub) was conducted from March till July 2022 using following keywords: "edible insect," "beef," "nutritional value," "nutrition," "nutritive". Articles on edible insects and beef were retrieved, with edible insects as the group of experiment and beef as the group of control. Preliminary searches identified 10,119 potential articles on edible insects and 10,735 on beef, with the full texts of inaccessible articles obtained through author correspondence. Selection criteria included publication dates, assessment of nutritional, environmental, and economic factors, availability of study data (mean values, standard deviation, replicates), description of the analytical methods used, and English language publication. The data for beef has been collected from 2018 to 2022 (5 years) and for edible insects from 2011 to 2022 (12 years). This approach was adopted to obtain the most recent data utilizing the latest analysis methods. The beef data from 2018 to 2022 were considered sufficiently homogeneous and representative for use. However, due to the inclusion of multiple species in edible insect research, additional data was required, leading to an extension of the data range from 2011 to 2022. Articles were excluded if they were irrelevant to the variables under investigation or if they lacked complete data. Specifically, some articles did not provide any information on the variables of interest, including nutritional, environmental, or economic aspects. Additionally, several articles were excluded due to the absence of essential data, such as mean values, replicates, and standard deviations, which were critical for conducting further data analysis.

Beef is commonly used as a reference in discussions about edible insects because of its established role as a primary source of high-quality protein and its broad cultural acceptance. Nutritionally, beef serves as a benchmark to assess the protein content, amino acid profile, and other essential nutrients in edible insects. Additionally, beef production has a substantial environmental impact, especially regarding greenhouse gas emissions, land use, and water consumption, making it an ideal comparison to highlight the sustainability benefits of insect farming, which requires fewer resources and generates lower emissions (Tanga et al., 2021). Economically, beef holds a prominent place in the global food industry, and comparing it with insects helps evaluate the cost-effectiveness, scalability, and market potential of insect-based protein (Liceaga 2021). Overall, using beef as a comparator allows for a clearer understanding of the nutritional, environmental, and economic trade-offs when viewing edible insects as a viable and sustainable alternative source of protein.

The systematic review process of edible insects and beef articles used was shown in Appendix 1. Out of 10,119 articles, 7317 were removed due to the initial duplication screening in the edible insect group. Following title and abstract screening, 2249 articles were excluded, with 593 eliminated during the second duplicate screening and 1655 eliminated since their content was inadequate for the study. A full-text review of 553 articles led to the exclusion of 319 articles due to irrelevant parameters, with 233 articles being discarded. The final study included 222 papers, of which 196 focused on nutritional aspects, 13 on environmental aspects, and 13 on economic aspects (Appendix 1). Appendix 1 also shows the details for the beef group. The final paper used in this study mainly focused on 196 articles on nutritional aspects.

The coding study involved various moderator variables, including insect origin, species, sampling method, and growth stage. Out of 10,119 articles reviewed, 196 articles included in the final analysis. Each article contributed multiple study codes—928 in total—focused on nutritional aspects of edible insects. Parameters like fat, SFA (Saturated Fatty Acid), MUFA (Mono Unsaturated Fatty Acid), PUFA (Polyunsaturated Fatty Acid), UFA (Unsaturated Fatty Acid), n-3 (Omega-3), and n-6 (Omega-6) were analyzed with standardized units for further data analysis, encompassing both short-chain and long-chain fatty acids due to their significance and data availability. It is important to acknowledge that the types of food and fat sources consumed can affect the balance of PUFA and SFA, with the ideal ratio for human health differing depending on the source (Chaves et al., 2019; Simopoulos, 2016). Cao et al. (2022) meta-analysis showed that foods rich in MUFAs may help in modifying the blood lipid profile. UFA are also essential in animal diets as they cannot synthesize these molecules through their own metabolism (Kouba and Mourot, 2011). Empirical data also show that supplementing dairy cows' diets with unsaturated fatty acids enhances both the quantity and quality of milk fat production (Girón et al., 2016).

2.2. Statistical analysis

The present study used random effect and mixed model statistical approaches to compare different insect groups. St-Pierre (2001) described the mixed model approach as employing the PROC MIXED procedure using SAS 9.4 software from SAS Institute Inc., Cary, NC, USA. Various edible insects were considered fixed effects, while different research methods were considered random effects. The models were mixed model of meta-analysis (Irawan et al., 2021; St-Pierre, 2001). The statistical model was based on p-values. Each edible insect's p-value was <0.05, suggesting significant findings. Duncan's test was used to compare a variety of insects.

In the random effect method, the Hedges' d effect size was applied to measure the differences in each parameter examined (Hedges and Olkin, 1985; Koricheva et al., 2013; Palupi et al., 2012; Spake and Doncaster, 2017). Beef was designated as the control group, and edible insects as the experimental group. The effect size (d) was computed by multiplying the correction factor (J) by the average difference between the control and experimental groups, using the pooled standard deviation (S). The sample size for both the control group (C) and experimental group (E) is denoted by N.

$$d\ (effect\ size) = \frac{\underline{X}^E - \underline{X}^C}{S}\ J \tag{1}$$

As a note that $\underline{X}$ represents the average values of each group. A positive value of effect size indicates that the observed parameter value is higher in the control group, vice versa. J acts as a correction factor for small sample sizes, which is necessary for the standard random effect model applied in this meta-analysis.

$$J\ (correction\ factor) = 1 - \frac{3}{(4(N^C + N^E - 2) - 1)} \tag{2}$$

$$S\ (SD\ pooled) = \sqrt{\frac{(N^E - 1)(s^E)^2 + (N^C - 1)(s^C)^2}{(N^E + N^C - 2)}} \tag{3}$$

The formula for Hedges' d variance (Vd) is a sampling variance: $wi = 1/V_d$. While cumulative effect size (d_{++}) was calculated using 95 % confidence interval (CI) to describe the effect size precision, where $d_{++} \pm (1.96 \times S_d)$. It is considered significant if CI value failed to achieve zero-effect size.

$$V_d(variance) = \frac{N^C + N^E}{N^C N^E} + \frac{d^2}{(2(N^C + N^E))} \tag{4}$$

$$d_{++}(effect\ size\ kumulatif) = \frac{\left(\sum_{i=1}^{n} w_i d_i\right)}{\left(\sum_{i=1}^{n} w_i\right)}. \tag{5}$$

An assessment of heterogeneity, publication bias, and study robustness was also conducted to guide the decision for performing a subgroup analysis within the studies and to estimate the number of unpublished or insignificant studies that were excluded from the analysis. Fragkos et al. (2014) utilized funnel plots to examine publication bias. The robustness of the study was evaluated using the fail-safe number (NR) method, as outlined by Fragkos et al. (2014) and Rosenthal (1979).

$$N_R = \frac{\left(\sum_{i=1}^{n} Z_i\right)^2}{Z_\alpha^2} - k. \tag{6}$$

k is the number of studies or articles and Zα is to determine the necessary degree of alpha significance. When the fail-safe number (NR) exceeds 5k+10, the risk of publication bias is considered low. To interpret the effect size, Cohen's benchmark was applied, categorizing it into three levels: small ($d = 0.2$), moderate ($d = 0.5$), and large ($d = 0.8$). The

Hedges' d analysis was performed using the OpenMEE application.

3. Results

This study is a follow-up evaluation of a meta-analysis performed by Nasir et al. (2024). The current assessment focused on the fatty acid content from 10 most prevalent edible insects, i.e.: (1) Mealworm (*Tenebrio molitor*), (2) BSF (*Hermetia illucens*), (3) house cricket (*Acheta domesticus*), (4) Mulberry silkworm (*Bombyx mori*), (5) long-horned grasshopper (*Ruspolia differens*), (6) Red palm weevil (*Rhynchophorus ferrugineus*), (7) Ground cricket *Henicus whellani*), (8) African palm weevil (*Rhynchophorus phoenicis*), (9) Lesser mealworm *Alphitobius diaperinus*, and (10) Chafer beetle (*Eulepida mashona*). Among the edible insect species examined, comprehensive data are available for four species: Mealworm, Mulberry Silkworm, Long-Horned Grasshopper, and Palm Weevil. This study provides an in-depth analysis of the fatty acid composition of these species, including the major fatty acid groups as well as the specific fatty acids categorized by chain length (short, medium, and long). A comparison of their fatty acid profiles with those of beef is also presented, and the potential of these insects as substitute fat sources in animal feed formulations is highlighted.

3.1. Fatty acids of the 10 chosen edible insects as sustainable fat food

Eight key fatty acid parameters were analyzed as indicators of fatty acids quality, including SFA, MUFA, PUFA, UFA, n-3, n-6, as well as the PUFA/SFA ratio and the n-6/n-3 ratio, as detailed in Table 1. The ten edible insect species studied were classified based on their fat content, which ranged from 8 to 50 %. The African palm weevil exhibited the highest fat content at 50.88 %, followed by the Red palm weevil at 38.03 %, the Long-horned grasshopper at 36.53 %, and the Mealworm at 30.06 %. The fat content categories were defined as follows: (1) 'Low fat' for fat < 3 g/100 g, (2) 'Medium fat' for fat 3–7 g/100 g, (3) 'Source of fat' for fat 7–15 g/100 g, and (4) 'High fat' for fat > 15 g/100 g (Schwingshackl et al. 2021). Consequently, all the edible insects in this study were classified as either sources of fat or high-fat commodities. The Ground cricket and Chafer beetle, with fat contents of 8.5 % and 11.7 %, respectively, were categorized as sources of fat. The remaining species, including Mealworm, BSF, House cricket, Mulberry silkworm, Long-horned grasshopper, Red palm weevil, African palm weevil, and Lesser mealworm, were classified as high-fat edible insects, therefore, they could serve as a potential fat source for both food and feed.

The findings from the mixed-model meta-analysis indicated notable differences in the fatty acid profiles across the ten edible insect species examined, particularly highlighting the ratios of polyunsaturated fatty acids (PUFA) to saturated fatty acids (SFA). Specifically, Mealworm, Mulberry silkworm, and Long-horned grasshopper were identified as having the highest levels of UFA, constituting 73.4 %, 68.6 %, and 63.7 % of their total lipid content, respectively. Notably, the Mulberry silkworm exhibited the highest omega-3 fatty acid content, accounting for 13.7 % of its total lipids or 2.58 g/100 g (wb). It is well established that adults require 1.1 g/d of omega-3 for women and 1.6 g/d for men (NIH 2022). Therefore, consuming a single serving of Mulberry silkworm (40–60 g) can sufficiently meet the daily omega-3 needs of an adult. Across all species analyzed, myristoleic acid, palmitic acid, and oleic acid emerged as the predominant fatty acids. When these fatty acid proportions were recalculated based on the initial fat content, African palm weevil, Long-horned grasshopper, and Red palm weevil were found to have the highest concentrations of unsaturated fatty acids, measuring 23.28, 19.33, and 27.29 % (wb), respectively.

These findings highlight the nutritional value of edible insects as a source of healthy fats, which can significantly contribute to human diets. Fatty acids are crucial dietary components due to their diverse effects on health. A balanced intake of various fatty acids is essential for maintaining overall well-being and preventing chronic diseases. For example, omega-3 fatty acids, commonly found in fish, flaxseeds, and walnuts, are renowned for their cardiovascular benefits. Research has demonstrated that omega-3 s, including EPA (eicosapentaenoic acid) and DHA (docosahexaenoic acid), help reduce inflammation, lower lipid levels, and decrease the risk of heart disease (Bhatt et al., 2020). Additionally, these fatty acids are vital for brain health and cognitive function, as they play a key role in the structure and functioning of neuronal membranes. Omega-3 deficiencies have been associated with cognitive decline and mood disorders (Dyall, 2015; Sun et al., 2018).

The balance between omega-6 and omega-3 fatty acids is vital for managing inflammation. Excessive omega-6 intake, especially from processed oils, can contribute to chronic inflammation. Maintaining an optimal ratio of these fatty acids is crucial for reducing inflammation and promoting health (Chaves et al., 2019; Simopoulos, 2016). Fatty acids also support cell membrane structure and fluidity, which is essential for proper cell function and communication. Additionally, essential fatty acids like linoleic acid and alpha-linolenic acid are

Table 1
Fatty acids profile from world top 10 most researched edible insects.

FA (% Total Lipid)	Mealworm T. Molitor	BSF H. illucens	House cricket A. domesticus	Mulberry silkworm B. mori	Long-horned grasshopper R. differens	Red palm weevil R. ferrugineus	Ground cricket H. whellani	African palm weevil R. phoenicis	Lesser mealworm A. diaperinus	Chafer beetle E. mashona
Fat (g/100 g wb)	30.06 $\pm1.27^{bc}$	20.41 $\pm0.74^{d}$	18.65 $\pm0.55^{de}$	18.80 $\pm0.43^{de}$	36.53 ± 3.01^{b}	38.03 ± 1.21^{b}	8.47 ± 0.36^{f}	50.58 ± 1.39^{a}	25.43 $\pm0.84^{cd}$	11.68 $\pm0.60^{ef}$
SFA	25.15 $\pm1.11^{d}$	70.82 $\pm1.18^{a}$	32.07 $\pm0.98^{cd}$	31.37 ± 1.73^{cd}	35.18 ± 2.65^{c}	38.51 $\pm1.23^{bc}$	NA	46.00 ± 2.30^{b}	33.84 $\pm2.99^{cd}$	NA
MUFA	44.59 $\pm1.49^{a}$	14.60 $\pm0.57^{d}$	25.43 $\pm0.55^{c}$	27.14 ± 1.99^{c}	44.65 ± 2.23^{a}	41.29 ± 1.86^{a}	NA	41.82 ± 1.85^{a}	34.41 ± 1.68^{b}	NA
PUFA	29.03 $\pm1.27^{b}$	14.25 $\pm0.58^{cd}$	41.86 $\pm1.17^{a}$	42.10 ± 2.63^{a}	20.15 ± 2.09^{c}	10.66d $\pm1.09^{de}$	NA	4.54 ± 0.38^{e}	30.99 ± 1.77^{b}	NA
UFA	73.39 $\pm0.28^{a}$	NA	NA	68.64 $\pm5.09^{ab}$	63.72 ± 2.26^{b}	50.84 ± 2.20^{c}	NA	53.96 ± 2.30^{c}	NA	NA
PUFA/SFA	1.29 ± 0.01^{a}	0.13 $\pm0.01^{c}$	1.31*	1.34*	0.56 ± 0.03^{b}	0.16 ± 0.01^{c}	NA	0.01*	1.05 ± 0.01^{a}	NA
n-3	1.23 ± 0.67^{b}	0.70 $\pm0.10^{b}$	1.89 ± 0.09^{b}	13.72 ± 0.65^{a}	1.23 ± 0.17^{b}	3.82 ± 0.14^{b}	NA	NA	NA	NA
n-6	27.89 $\pm0.95^{b}$	8.15 $\pm0.20^{cd}$	39.12 $\pm0.57^{a}$	3.46 ± 0.18^{d}	15.84 ± 1.02^{c}	6.7 ± 0.17^{d}	NA	NA	NA	NA
n-6/n-3	26.24 $\pm1.72^{a}$	3.33 $\pm0.12^{b}$	28.55 $\pm2.10^{a}$	0.25*	14.59 ± 1.64^{ab}	3.54 ± 0.36^{b}	NA	3.33 ± 0.12^{b}	17.90 $\pm0.35^{ab}$	NA

FA, Fatty Acids; wb, wet basis; SFA, Saturated Fatty Acid; MUFA, Mono Unsaturated Fatty Acid; PUFA, Ply Unsaturated Fatty Acid; UFA, Unsaturated Fatty Acid; n-3, Omega 3; n-6, Omega 6; NA, data is not available. *data manually calculated from the available data in the table.

precursors to hormones that regulate metabolism, inflammation, and reproduction. A diet rich in healthy fats from sources like nuts, seeds, avocados, and fatty fish can enhance overall health and lower the risk of chronic diseases like obesity, type 2 diabetes, and certain cancers (Chaves et al., 2019; Simopoulos, 2016).

In summary, the composition of fatty acids in our daily diet is essential for obtaining the nutrients necessary for optimal health, supporting heart health, brain function, reducing inflammation, and preventing chronic diseases (Chaves et al., 2019). This study highlights the potential of edible insects as a valuable source of unsaturated fatty acids, which can be incorporated into the diet to enhance health outcomes.

The optimal ratio of PUFA (Polyunsaturated Fatty Acids) to SFA (Saturated Fatty Acids) for human health varies based on the source. Typically, a PUFA to SFA ratio of 1:1 or higher is recommended, with an emphasis on consuming PUFA, particularly omega-3 and omega-6 fatty acids, due to their association with health benefits such as reduced heart disease risk and inflammation (Simopoulos, 2016). The Mulberry silkworm, House cricket, Mealworm, and Lesser mealworm meet the recommended PUFA to SFA ratios, with values of 1.34, 1.31, 1.29, and 1.05, respectively.

However, it is important to recognize that the type of food and fat sources consumed can influence the balance between PUFA and SFA (Chaves et al., 2019; Simopoulos, 2016). For example, animal fat sources tend to have higher SFA content, while plant fat sources tend to be richer in PUFA (Chaves et al., 2019). Most dietary guidelines recommend limiting SFA intake from sources such as animal fats and high-fat processed products while increasing PUFA consumption from healthy sources like fish, nuts, and vegetable oils (Chaves et al., 2019). Therefore, based on this current meta-analysis, some edible insects, such as Mulberry silkworm, House cricket, Mealworm and Lesser mealworm might support keeping the balance ratio of PUFA and SFA from food intake.

Humans evolved on a diet with a 1:1 omega-6 to omega-3 ratio, but modern Western diets have a ratio of 15:1 to 16.7:1, leading to an omega-3 deficiency and excess omega-6 (Simopoulos, 2016). This imbalance is linked to diseases like cardiovascular disease, cancer, and autoimmune disorders (Calder, 2015; Chaves et al., 2019). Studies show that lower omega-6/omega-3 ratios, such as 4:1, reduce cardiovascular

Table 2
Fatty acids composition from world top 10 edible insects.

FA (% Total Lipid)	Mealworm T. Molitor	BSF H. illucens	House cricket A. domesticus	Mulberry silkworm B. mori	Long-horned grasshopper R. differens	Red palm weevil R. ferrugineus	Ground cricket H. whellani	African palm weevil R. phoenicis	Lesser mealworm A. diaperinus	Chafer beetle E. mashona
Caprylic acid (C8:0)	0.02±0.01^{c}	NA	NA	NA	0.22±0.07^{b}	1.05±0.02^{a}	NA	NA	NA	NA
Decanoic acid (C10:0)	0.03 ±0.003^{b}	1.26 ±0.10^{a}	NA	NA	0.07±0.03^{b}	0.08±0.004^{b}	NA	NA	NA	NA
C11:0	NA	NA	NA	NA	NA	0.08±0.02	NA	NA	NA	NA
Lauric acid (C12:0)	0.46±0.06^{b}	30.88 ±1.14^{a}	0.09±0.02^{b}	NA	0.10±0.02^{b}	0.17±0.02^{b}	NA	2.28±0.16^{b}	0.09±0.02^{b}	NA
C13:0	0.08±0.01^{a}	NA	NA	NA	0.10±0.02^{a}	0.02±0.001^{b}	NA	NA	0.02±0.01^{b}	NA
Myristic acid (C14:0)	4.39±0.31^{a}	4.05 ±0.13^{a}	0.71 ±0.06^{bc}	0.16±0.01^{c}	1.63±0.36^{bc}	2.15±0.14^{b}	NA	2.36±0.21^{b}	0.85±0.09^{bc}	NA
Myristoleic (C14:1)	0.014 ±0.008^{b}	NA	0.03±0.001	NA	0.07±0.02^{a}	0.09±0.02^{a}	NA	NA	NA	NA
C15:0	0.13 ±0.02^{ab}	0.16 ±0.01^{ab}	0.10±0.01^{b}	NA	0.09±0.02^{b}	0.12±0.01^{ab}	NA	0.13±0.03^{ab}	0.21±0.14^{a}	NA
C15:1 (cis-10)	NA	NA	NA	NA	NA	0.30±0.06	NA	NA	NA	NA
Palmitic acid (C16:0)	17.45 ±0.60^{c}	10.76 ±0.38^{d}	23.84 ±0.66^{b}	23.27 ±0.96^{b}	27.07±1.61^{b}	32.28±1.19^{a}	NA	28.06 ±1.22^{ab}	23.66 ±1.58^{b}	NA
Hypogeic acid (C16:1n-7)	2.57 ±0.12^{ab}	0.42 ±0.01^{b}	NA	0.76±0.04^{ab}	6.06±1.43^{a}	NA	NA	3.45±0.17^{ab}	NA	NA
Palmitoleic acid (C16:1) (cis-9)	1.64±0.10^{b}	1.03 ±0.04^{b}	1.03±0.08^{b}	NA	NA	7.57±0.30^{a}	NA	1.41±0.11^{b}	0.50±0.02^{b}	NA
Palmitoleic acid (C16:1) (trans)	1.02±0.04	NA	0.51±0.06	NA	NA	NA	NA	NA	NA	NA
C17:0	0.13±0.02^{b}	0.30 ±0.01^{ab}	0.27 ±0.02^{ab}	NA	0.21±0.03^{ab}	0.16±0.05^{b}	NA	NA	0.48±0.04^{a}	NA
C17:1n-7	0.18±0.03	NA	NA	NA	NA	NA	NA	NA	NA	NA
C17:1 (cis-10)	0.14 ±0.01^{ab}	NA	0.07 ±0.04^{bc}	NA	NA	0.05±0.04^{c}	NA	NA	0.15±0.07^{a}	NA
Stearic acid (C18:0)	3.76±0.21^{c}	3.30 ±0.11^{c}	6.73±0.36^{b}	7.94±0.41^{b}	7.49±0.88^{b}	2.23±0.15^{c}	NA	11.38 ±0.54^{a}	8.40±0.68^{b}	NA
Oleic acid (C18:1 n-9)	43.52 ±0.99^{a}	19.25 ±0.39^{e}	26.89 ±0.78^{cd}	25.78 ±1.70^{de}	39.70±2.06^{ab}	38.52 ±1.37^{ab}	NA	34.50 ±1.25^{b}	33.83 ±1.47^{bc}	NA
C18:1n-11	5.05±0.14	1.08 ±0.06	1.71±0.45	NA	NA	NA	NA	NA	0.40±0.01	NA
Elaidic acid (C18:1) (trans)	43.77 ±1.62^{a}	NA	NA	NA	0.09±0.02^{c}	NA	NA	NA	0.20±002^{b}	NA
Oleic acid (C18:1) (*cis*)	40.5 ± 0.73^{a}	9.7 ± 0.20^{b}	NA	NA	NA	NA	NA	NA	35.9 ± 0.30^{a}	NA
Linoleic acid (C18:2 n-6)	23.72 ±1.10^{bc}	21.19 ±0.45^{c}	32.06 ±0.78^{a}	7.63±0.41^{e}	15.40±2.12^{d}	5.07±0.29^{e}	NA	4.10±0.38^{e}	27.50 ±1.09^{ab}	NA
ALA (C18:3n-3)	1.07±0.07^{c}	9.17 ±0.22^{b}	3.78±0.21^{c}	34.27 ±1.43^{a}	1.05±0.25^{c}	3.20±0.14^{c}	NA	1.50±0.08^{c}	3.66±0.53^{c}	NA
y-Linoleic acid (C18:3 all-cis-*cis* 6.9.12)	0.51±0.01^{a}	NA	0.26±0.02^{b}	NA	NA	0.08±0.03^{c}	NA	NA	0.10±0.04^{bc}	NA
C19:0	0.10±0.01^{c}	NA	NA	NA	0.16±0.03^{b}	NA	NA	NA	0.20±0.02^{a}	NA

FA, Fatty Acids; SFA, Saturated Fatty Acid; MUFA, Mono Unsaturated Fatty Acid; PUFA, Ply Unsaturated Fatty Acid; UFA, Unsaturated Fatty Acid; n-3, Omega 3; n-6, Omega 6; NA, data is not available.

mortality by 70 %, while a 2.5:1 ratio helps reduce colorectal cancer cell proliferation (Dyall, 2015). A lower ratio is beneficial for managing diseases common in Western societies (Simopoulos, 2002).

The optimal omega-6 to omega-3 ratio for human health is generally considered to be between 4:1 and 1:1 (Chaves et al., 2019), meaning omega-6 should ideally be consumed four times more than omega-3. This ratio helps maintain the balance of the body's inflammatory response and supports cardiovascular and brain health (Chaves et al., 2019). However, individual health conditions, diet, lifestyle, and genetics can influence this ratio. Based on this guideline, Mulberry silkworm, African palm weevil, BSF, and red palm weevil have the appropriate n-6/n-3 ratio.

3.1.1. Fatty acids composition

Furthermore, as many as 25 fatty acids also elucidated in this paper. Those fatty acids are Caprylic acid (C8:0), Decanoic acid (C10:0), C11:0, Lauric acid (C12:0), C13:0, Myristic acid (C14:0), Myristoleic (C14:1), C15:0, C15:1 (cis-10), Palmitic acid (C16:0), Hypogeic acid (C16:1n-7), Palmitoleic acid (C16:1 cis-9), Palmitoleic acid (C16:1 trans), C17:0, C17:1n-7, C17:1 (cis-10), Stearic acid (C18:0), Oleic acid (C18:1 n-9), C18:1 n-11, Elaidic acid (C18:1 trans), Oleic acid (C18:1 *cis*), Linoleic acid (C18:2 n-6), ALA (C18:3 n-3), y-Linoleic acid (C18:3 all-cis-*cis* 6.9.12), and C19:0 (presented on Table 2).

Myristoleic acid, palmitic acid, and oleic acid emerges as the predominant component contained in edible insects (Table 2). Compared with beef, some edible insects seem promising for providing nutritious fatty acid profiles. Moreover, these favourable profiles deliver some expected advantages for further utilisation as feed. These advantages could be from nutritional and environmental aspects so that produce more nutritious livestock with lower greenhouse gas emissions (van Huis, 2020). More studies are needed to promote indigenous edible insect products as nutritious food and feed (Preyer and Davidowitz 2021).

Nearly all the edible insects studied exhibited a characteristic fatty acid profile dominated by myristic acid (C14:0). This fatty acid, in conjunction with lauric acid (C12:0), can serve as a valuable source of oil supplements for ruminants, which has been shown to reduce methane emissions—a major contributor to global warming (Jayanegara et al., 2017). Additionally, palmitic acid (C16:0), oleic acid (C18:1 n-9), elaidic acid (C18:1) (trans), oleic acid (C18:1) (*cis*), and linoleic acid (C18:2 n-6) are the predominant fatty acids found in the ten edible insects analyzed in this meta-analysis. C16 and C18 fatty acids, with an energy yield of 9 kcal/g, are effective sources of energy (FAO, 2008), making them suitable for addressing malnutrition in populations where edible insects like mealworms and grasshoppers are culturally accepted. These fatty acids also hold significant potential in supporting the energy needs of livestock, a common challenge for enhancing livestock productivity and quality (van Huis, 2020; van Huis et al., 2013). Notably, the black soldier fly (BSF) exhibits a fatty acid composition that is particularly well-suited for livestock feed, with high levels of C12 and C14 acids that are effective in reducing methane emissions (Elahi et al., 2022). Furthermore, BSF is rich in C16 and C18 fatty acids, making it an excellent energy source to boost livestock productivity (van Huis, 2020; van Huis et al., 2013). BSF contains a high portion of lauric acid (C12) about 30 %. Those favored profiles deliver some expected advantages to further utilize as feed (Liland et al., 2021; Liceaga 2021). These advantages could be from nutritional and environmental aspects so that produce more nutritious livestock with lower greenhouse gas emissions.

3.1.2. Long-chain fatty acid composition of top 10 edible insects

Further evaluation on the longer fatty acids which is $\geq$ 20 Carbon was also performed on this study. Those fatty acids are Arachidic acid (C20:0), Gondoic acid (C20:1), C20:2 (11.14), C20:3 (all-cis-8.11.14), C20:3 (all-cis-11.14.17), Arachidonic acid (C20:4 n6) (ARA), Eicosapentaenoic C20:5 (all-*cis* 5.8.11.14.17) (EPA), C21:0, C21:1 (11), Docosanoic (C22:0), C22:1n-9 (DPA), C22:1 (13), cis-13.16-docosadienoic acid, C22:2 (all-*cis* 13.16), C22:6 (all-cis-4.7.10.13.16.19) (DHA), C23:0, Lignoceic (C24:0), and Osenic C24:1 (15) (presented on Table 3). The study on the profile of the long-chain fatty acid composition of top 10 edible insects provides a picture that this part not yet much explored during the last two decades. Even so, the key parameters on fatty acids profile i.e., essential fatty acids like EPA, DHA, and DPA were mostly the data is not available.

Results confidently present that some edible insects like *mealworm* contain omega-3 PUFA with quite significant proportions, particularly C21:1 (11) with 30.22 % from total fat. Regarding the composition of long-chain fatty acids, the black soldier fly (BSF) exhibits a distinctive feature with a C22:1 (13) content reaching up to 15.20 % of the total fat composition. The functional implications of this fatty acid, particularly in terms of its potential benefits as livestock feed, including productivity, product quality, and environmental impact, warrant further investigation (van Huis, 2020). Meanwhile, the long-horned grasshopper displays a unique profile with notable long-chain fatty acids, namely arachidonic acid (ARA) at 0.4 % and eicosapentaenoic acid (EPA) at 0.52 %, both of which are closely linked to cognitive function (von Schacky, 2021). This finding strengthens the case for utilizing grasshoppers as a food source, given their clear halal status and cultural acceptance, especially among older generations, compared to other edible insects (Palupi et al., 2020). Additionally, research by Labu et al. (2022) reported that no contaminants were detected in edible long-horned grasshoppers, indicating the potential for food safety assurance in this species as an edible insect. Another unique characteristic was found in the African palm weevil, which has a prominent long-chain fatty acid profile, including arachidonic acid (AA) at 2.56 %, docosanoic acid (C22:0) at 1.26 %, C22:1 (13) at 3.05 %, and lignoceric acid (C24:0) at 2.71 %. The lesser mealworm also shows a unique fatty acid composition with C21:1 (11) reaching up to 0.52 %. However, these unique fatty acid compositions require further study, as they have not been extensively explored in other research.

3.1.3. Fatty acid of 10 edible insects compared with beef

Comparison study using effect size method was also performed using Hedges'd effect size method. The content comparison of ALA, ARA, MUFA, PUFA, EPA, DHA, n-3, and n-6 between the 10 most researched edible insects and beef are presented on Fig. 1 and 2. Compared with beef, some edible insects seem promising for providing nutritious fatty acid profiles.

4. Discussion

4.1. Edible insects as an alternative fat source for food

In comparison to traditional animal farming, insect farming requires substantially less area, water, and feed (FAO, 2021). Insects also emit fewer greenhouse emissions and generate fewer waste products (Dobermann et al., 2017; Oonincx and de Boer, 2012). We could help minimize the environmental impact of food production and agriculture by enhancing insect consumption. Insects are extremely efficient at turning feed into edible biomass. Crickets, for example, can convert feed into body mass at around a 2:1 ratio, but cattle require substantially more feed to generate the same quantity of meat (FAO, 2021). This efficiency enables insect farming a more resource-efficient and sustainable alternative to traditional animal production. Promoting the consumption of edible insects can assist lessen pressure on wild fish and game populations, alleviating overfishing, and habitat degradation (van Huis, 2015). Additionally, many edible insect species can be farmed using organic waste materials, providing a sustainable solution for recycling organic waste and reducing pollution.

Edible insects are a rich source of protein, vitamins, minerals, and healthy fats. Incorporating insects into the diet can help address malnutrition and food insecurity, especially in regions where access to affordable and nutritious food is limited (van Huis, 2015). Insects also offer a sustainable protein source for feeding livestock, which can help

Table 3
Long-chain fatty acids composition from world top 10 edible insects.

FA (% Total Lipid)	Mealworm	BSF	House cricket	Mulberry silkworm	Long-horned grasshopper	Red palm weevil	Ground cricket	African palm weevil	Lesser mealworm	Chafer beetle
	T. Molitor	H. illucens	A. domesticus	B. mori	R. differens	R. ferrugineus	H. whellani	R. phoenicis	A. diaperinus	E. mashona
Arachidic acid (C20:0)	0.14 ± 0.02^{b}	1.04 ± 0.07^{b}	0.41 ± 0.04^{b}	NA	0.61 ± 0.29^{b}	0.11 ± 0.02^{b}	NA	2.56 ± 0.28^{a}	0.34 ± 0.03^{b}	NA
Gondoic acid (C20:1)	0.16 ± 0.01^{ab}	0.21 ± 0.03^{a}	0.06 ± 0.01^{b}	NA	NA	NA	NA	NA	NA	NA
C20:2 (11.14)	0.11 ± 0.01	NA	0.11 ± 0.007	NA	NA	0.28 ± 0.04	NA	NA	0.12 ± 0.03	NA
C20:3 (all-cis-8.11.14)	NA	NA	0.06 ± 0.01	NA	NA	0.07 ± 0.03	NA	NA	0.15 ± 0.08	NA
C20:3 (all-cis-11.14.17)	0.20 ± 0.04^{a}	NA	0.04 ± 0.03^{c}	NA	NA	0.04 ± 0.02^{c}	NA	NA	0.11 ± 0.07^{b}	NA
Arachidonic acid (C20:4 n6) (ARA)	0.32 ± 0.06	0.20 ± 0.01	0.11 ± 0.05	NA	0.40 ± 0.09	0.22 ± 0.04	NA	NA	0.20 ± 0.08	NA
Eicosapentaenoic C20:5 (all-*cis* 5.8.11.14.17) (EPA)	NA	NA	0.03 ± 0.003	NA	0.52 ± 0.06	0.16 ± 0.09	NA	NA	NA	NA
C21:0	NA	NA	0.15 ± 0.005^{b}	NA	0.05 ± 0.03^{b}	0.03 ± 0.003^{b}	NA	NA	0.52 ± 0.01^{a}	NA
C21:1 (11)	30.22 ± 0.01	NA	0.25 ± 0.02	NA	NA	NA	NA	NA	0.38 ± 0.03	NA
Docosanoic (C22:0)	0.17 ± 0.01^{b}	0.65 ± 0.03^{ab}	0.03 ± 0.003^{b}	NA	0.05 ± 0.02^{b}	0.06 ± 0.005^{b}	NA	1.26 ± 0.10^{a}	0.09 ± 0.008^{b}	NA
C22:1n-9 (DPA)	1.18 ± 0.19^{b}	0.38 ± 0.10^{b}	NA	NA	NA	NA	NA	3.05 ± 0.32^{a}	NA	NA
C22:1 (13)	0.11 ± 0.03	15.20 ± 0.48	NA	NA	NA	NA	NA	NA	0.39 ± 0.02	NA
cis-13.16-docosadienoic acid C22:2 (all-*cis* 13.16)	0.08 ± 0.01^{c}	NA	0.13 ± 0.01^{b}	NA	NA	0.05 ± 0.03^{d}	NA	NA	0.25 ± 0.03^{a}	NA
C22:6 (all-cis-4.7.10.13.16.19) (DHA)	0.17 ± 0.01^{b}	NA	NA	NA	0.77 ± 0.11^{a}	0.04 ± 0.004^{c}	NA	NA	NA	NA
C23:0	0.20 ± 0.03^{a}	NA	0.14 ± 0.03^{ab}	NA	NA	0.03 ± 0.003^{b}	NA	NA	0.11 ± 0.01^{ab}	NA
Lignoceric (C24:0)	0.18 ± 0.01^{bc}	0.31 ± 0.01^{b}	0.08 ± 0.01^{c}	NA	0.05 ± 0.006^{c}	0.06 ± 0.006^{c}	NA	2.71 ± 0.13^{a}	NA	NA
Osenic C24:1(15)	NA	0.64 ± 0.02^{a}	0.29 ± 0.01^{ab}	NA	NA	0.21 ± 0.17^{ab}	NA	NA	0.04 ± 0.004^{b}	NA

FA, Fatty Acids; SFA, Saturated Fatty Acid; MUFA, Mono Unsaturated Fatty Acid; PUFA, Ply Unsaturated Fatty Acid; UFA, Unsaturated Fatty Acid; n-3, Omega 3; n-6, Omega 6; NA, data is not available.

reduce the reliance on unsustainable soy and fishmeal in animal feed. Insect farming can provide livelihood opportunities for small-scale farmers, particularly in developing countries (FAO, 2021). In many cultures, insects have been consumed as a traditional food source for centuries (Nasir and Świąder, 2022). By promoting cultural acceptance of edible insects and encouraging culinary innovation, we can expand the market for insect-based foods and create new opportunities for sustainable food production and consumption (Nasir and Świąder, 2022). Moreover, edible insects are more readily accepted in hot, dry areas with low rainfall due to limited food resources, cultural traditions, and the efficiency of insect farming in harsh environmental conditions (Anagonou et al., 2024).

Insects are rich in protein, essential amino acids, vitamins, and minerals, making them a nutritious feed option for livestock and aquaculture (Liland et al., 2021). They can provide a well-rounded nutritional profile that supports the growth and development of animals (van Huis, 2020; van Huis et al., 2013). Insect farming requires fewer resources compared to traditional livestock farming (FAO, 2021). Insects can be reared on organic waste materials, reducing the environmental footprint of animal feed production, and promoting circular economy principles (Heckmann et al., 2019; Meneguz et al., 2018; Niyonsaba et al., 2021). Insects are highly efficient at converting feed into body mass. They have a higher feed conversion efficiency compared to conventional livestock, meaning they require less feed to produce the same amount of biomass (FAO, 2021).

With the increasing demand for protein and the sustainability challenges associated with conventional protein sources like soy and fishmeal, insects offer a viable alternative protein source (Alfiko et al., 2022). They can help diversify protein feed sources and reduce the reliance on unsustainable feed ingredients. Insects can be produced in controlled environments, reducing the risk of disease transmission and contamination compared to conventional livestock farming (Elahi et al., 2022; FAO, 2021). This can contribute to safer and more hygienic feed production practices. Insect farming can provide economic opportunities for farmers, particularly in regions where resources are limited. Insect based products has been diversifying income sources and creating new markets for insect products, such as cricket flour, protein bars, and snacks (Nasir and Świąder, 2022), insect farming can contribute to poverty alleviation and rural development (Choi et al., 2024). However, challenges such as insufficient funding, seasonal fluctuations, lack of expertise, inadequate extension services, and limited processing technologies impede the growth of edible insect farming (Aigbedion-Atalor et al., 2024).

Moreover, some edible insects particularly from mealworm and weevil groups were proved to have desired fatty acid composition with dominant portions of PUFA and omega-3. Edible insects offer a promising alternative protein source with notable health benefits, particularly due to their unique fatty acid profiles (Perez-Santaescolastica et al., 2023). Not only are they valuable from an economic and environmental perspective, but they are also highly nutritious and may offer significant health benefits (Siddiqui et al., 2024). These insects are rich in polyunsaturated fatty acids (PUFAs), especially omega-3 and omega-6 fatty

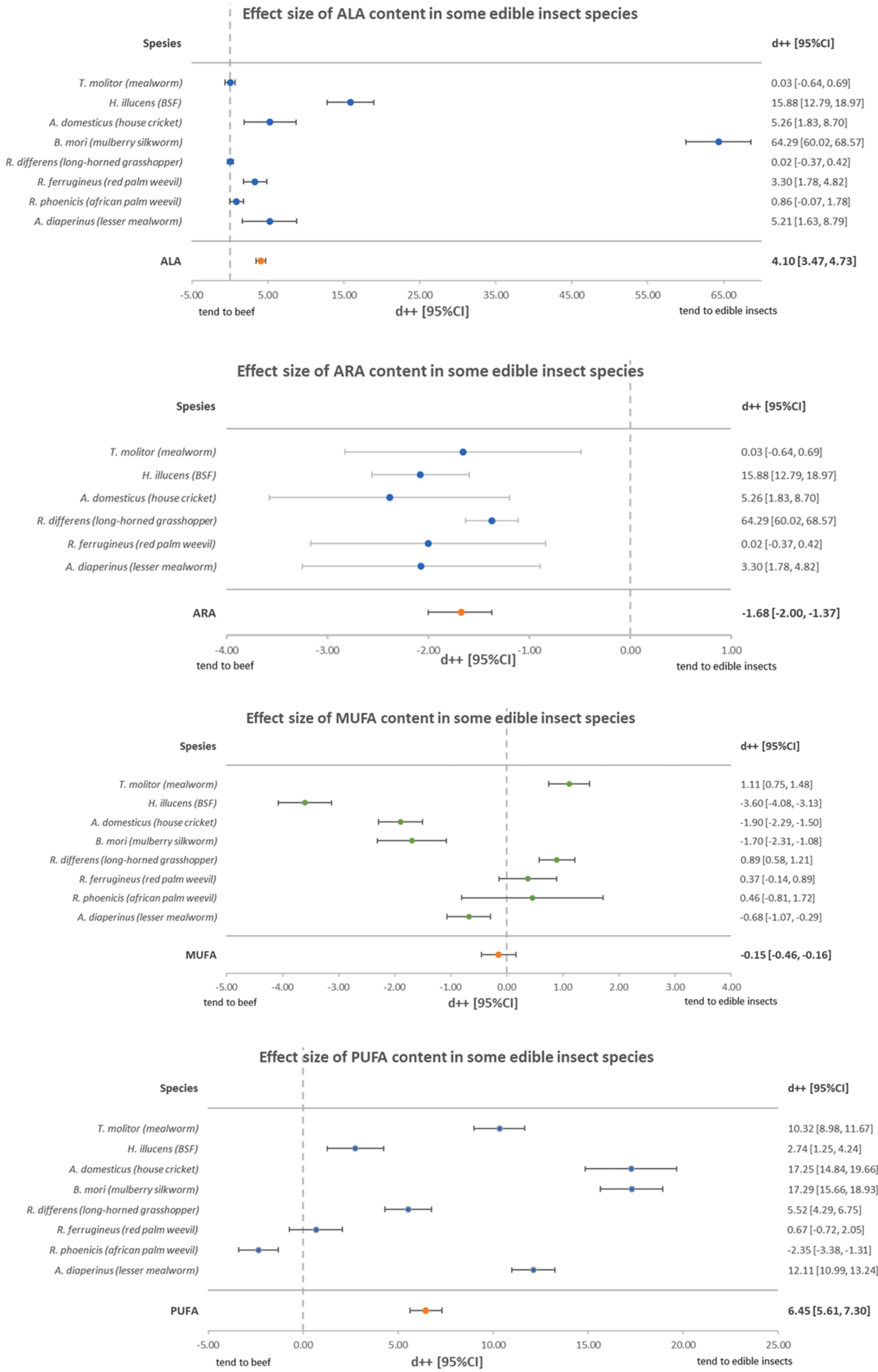

Fig. 1. Forest plot of ALA, ARA, MUFA and PUFA of selected edible insects' species compared with beef.

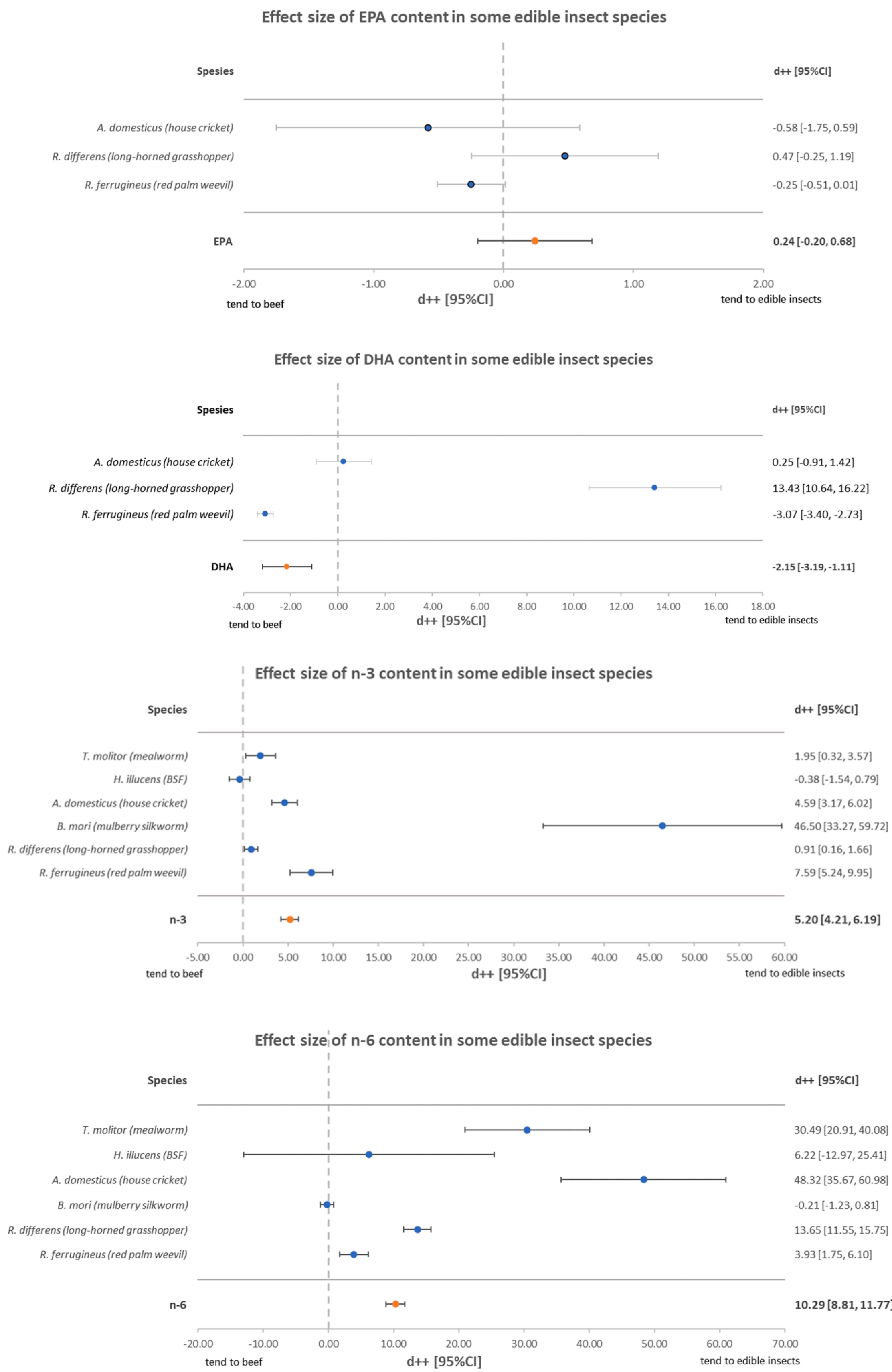

Fig. 2. Forest plot of EPA, DHA, omega-3 and omega-6 selected edible insects' species compared with beef.

acids, which are essential for cardiovascular health, cognitive function, and anti-inflammatory effects (Dyall, 2015; Freeman et al., 2006; Sun et al., 2018; von Schacky, 2021). Additionally, the favorable ratio of these fatty acids in edible insects contributes to a balanced diet, potentially reducing the risk of chronic diseases like heart disease and obesity. Incorporating edible insects into the diet can, therefore, support overall health by providing essential fatty acids that are often lacking in conventional diets (Choi et al., 2024; Amoah et al., 2023). Further research is warranted to explore the long-term health implications and optimal consumption levels of edible insects.

Despite such favorable fatty acid composition in edible insects, apart from the species-specific characteristics, their fatty acid profiles are contributed from the food or substrate that feeds the insects. In the case of black soldier fly larvae, for instance, it had been found that fatty acid composition of the substrate affected the fatty acid profile of the larvae (Ewald et al., 2020). In another study, Georgescu et al. (2022) highlighted the effects of a 10 % addition of vegetable oils from five dietary sources (i.e., linseed oil, soybean oil, sunflower oil, rapeseed oil, and hempseed oil) on the growth, development, reproductive performance, and the fat and fatty acids profile of black soldier fly larvae. It was revealed that the larvae fatty acid profile was different according to the oil type. Linseed oil inclusion led to the improvement of the unsaturated fatty acid profiles, especially in polyunsaturated fatty acids from the omega-3 groups, at 10 days age of larvae, followed by hempseed and rapeseed oil. Furthermore, Siddiqui et al. (2022) demonstrated that there was a positive correlation between the fatty acid concentration in the substrate and the concentration in black soldier fly larvae, which indicated that the concentration in the larvae is influenced by the concentration in the substrate. Similarly, fatty acid profiles of substrates heavily determined the fatty acid composition in mealworms (Rossi et al., 2022; Huang et al., 2025). All these results suggest that a main strategy to modify the fatty acid profiles in insects is by using substrates rich in the favourable fatty acids.

4.2. Insect oils as animal feed supplements

One of the challenges in supplying energy demand for livestock particularly in the tropical regions is the low energy contents of forages and the insufficient quality of concentrates (Ayele et al., 2021; Godde et al., 2021). This issue can be resolved by supplementing the livestock diet with a readily accessible and highly concentrated energy source, including oil or fat. In feed nutrition, the term "oil supplementation" is often preferred over "fat supplementation" because "oil" specifically refers to fats that are liquid at room temperature, making it more descriptive of the form being added to animal diets. "Fat" is a broader term that includes both solid and liquid forms. In many feed formulations, oils are used for their higher digestibility, palatability, and energy density compared to solid fats. Such high energy supplements are typically derived either from plant or animal origins such as coconut oil, palm oil, corn oil, canola oil, sunflower oil, animal fat or others. Oil serves as a source of energy, providing a calorie value that is 2.25 times greater than that of carbohydrates and protein. Additionally, oil creates substantially less metabolic heat (Sudarman et al., 2008). Insect oils are promising to be used as high energy supplements. The extraction of insects produces two distinct products, i.e., oil and high-protein insect meal. A number of studies have been conducted on the utilization of insect meal as a protein source in the diets of chicken (Elahi et al., 2022), fish (Alfiko et al., 2022), and ruminants (Bionaz et al., 2020). However, studies investigating the insect oils as energy supplements in livestock diets are presently still limited.

Regarding the fatty acid composition, insect oils are typically rich in MCFA and unsaturated fatty acids although the composition is varied according to many factors such as the insect species, developmental stage, substrate, environmental condition, etc. Unsaturated fatty acids are considered to be essentials in the diets of animals because they cannot produce the molecules from their own metabolism (Kouba and Mourot, 2011). However, in ruminants, their derived food products such as meat and milk contain relatively high levels of saturated fatty acids, which can have detrimental impacts on human health. Such facts occur due to the massive biohydrogenation process of unsaturated fatty acids in the rumen by various microbes, converting them to saturated fatty acids. Empirical data showed that supplementation of unsaturated fatty acids to the diet of dairy cows enhanced the quantity and quality of milk fat production (Girón et al., 2016). This included the increase of beneficial fatty acid profiles in milk, such as conjugated linoleic acid (CLA) and vaccenic acid (VA) (Gómez-Cortés et al., 2008). Conjugated linoleic acid (CLA) is a fatty acid with the potential to prevent a number of diseases due to its anti-obesity, anti-carcinogenic, anti-atherogenic, and anti-diabetogenic properties (Benjamin and Spener, 2009). Meanwhile, in beef cattle, dietary supplementation of unsaturated fatty acids affected the contents of unsaturated fatty acids in the meat products (Noosen et al., 2017), acted as defaunation agents in the rumen (Muktiani et al., 2020), and decreased methane gas production (Jayanegara et al., 2020).

Regarding their anti-methanogenic effects, unsaturated fatty acids can serve as an effective method to capture H_2 (hydrogen sinks), hence preventing the production of methane gas by methanogenic archaea (Pereira et al., 2022). Feeding animals with oil rich in unsaturated fatty acids also causes toxicity to protozoa, resulting in the death of numerous protozoa in the rumen (Thirumalaisamy et al., 2020). The lack of symbiotic interaction between protozoa and archaea due to the defaunation effect directly links to the decline in methane gas generation. Jayanegara et al. (2020) evaluated methane-mitigating properties of oils, under the in vitro rumen fermentation system, extracted from selected insect species, i.e., maggot, *kroto*, superworm, mealworm and cricket. C12:0 was the dominant fatty acid in maggot oil, but C18:1n-9 and C16:0 were the primary fatty acids in *kroto* oil. Superworm, mealworm, and cricket oils have high levels of C16:0, C18:1n-9, and C18:2n-6, respectively. The addition of all the insect oils was demonstrated to effectively reduce methane emissions in the high forage and high concentrate substrates, without altering total volatile fatty acid concentration. Among the insect oils, mealworm oil resulted in the lowest level of methane. In another study, maggot oil was proven to reduce the in vitro methane production as well (Prachumchai and Cherdthong, 2023).

The process of feed fermentation in the rumen generates volatile fatty acids (VFA), which serve as the primary energy source for ruminant livestock (Susanto et al., 2023). Fatty acid supplementation has a detrimental impact on rumen microbial activity and leads to a decrease in fiber digestibility (Jayanegara et al., 2017). However, Jalc et al. (2005) showed that adding 5 % MUFA and PUFA did not adversely affect rumen fermentation, and there was a tendency for a decrease in methane gas production. Candyrine et al. (2017) found no adverse effects on rumen fermentation when they added oil containing up to 4 % MUFA and PUFA. This occurrence is due to the mechanism that suppresses methane synthesis in ruminant animals through two distinct processes. The first process involves the indirect inhibition of fiber digestion, while the second process involves the direct inhibition of the growth and activity of methanogenic archaea (Tavendale et al., 2005). Therefore, when the feed used has a high level of digestibility, it will not impact the digestibility of the feed diet. According to this finding, fatty acids derived from insects can be utilized as feed additives to provide energy quickly, efficiently, and effectively in mitigating methane gas resulting from fermentation in the rumen.

5. Conclusion

This study provides compelling evidence that edible insects are a promising resource due to their advantageous fatty acid profiles, which contribute to improved nutritional status and health. Their integration into human diets and food systems can significantly advance sustainable development goals by offering a nutritious and eco-friendly alternative protein source. Furthermore, edible insects demonstrate exceptional potential in feed production, supporting animal growth and health while addressing critical environmental and economic challenges in agriculture. These findings underscore the suitability of edible insects as a viable and sustainable option for both human and animal consumption, highlighting their role in enhancing food security and fostering global agricultural sustainability.

CRediT authorship contribution statement

Eny Palupi: Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Syifa Q. Nasir:** Writing – review & editing, Software, Methodology, Investigation, Data curation. **Anuraga Jayanegara:** Writing – original draft, Methodology, Investigation, Funding acquisition, Conceptualization. **Irwan Susanto:** Writing – original draft, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Amin Ismail:** Writing – review & editing, Supervision, Conceptualization. **Ade Chandra Iwansyah:** Writing – review & editing, Resources, Conceptualization. **Budi Setiawan:** Writing – review & editing, Supervision, Conceptualization. **Ahmad Sulaeman:** Writing – review & editing, Supervision, Conceptualization. **M.Rizal M. Damanik:** Writing – review & editing, Supervision, Conceptualization. **Fitry Filianty:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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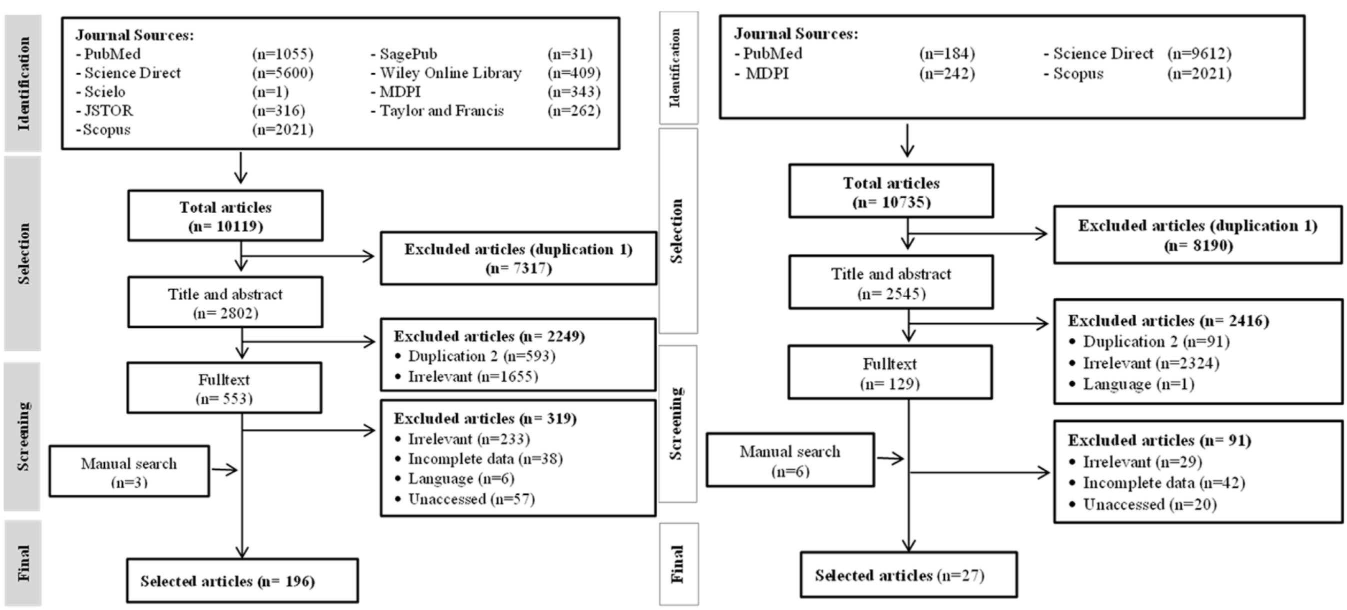
Appendix 1. Selected articles processing chart of edible insects (left) and beef (right, as control) (Nasir et al., 2024)



Data availability

Data will be made available on request.

References

Aigbedion-Atalor, P.O., Fening, K.O., Adeyemi, A.O., Idemudia, I., Ojukwu, K.C., Nwobodo, M.A., Sunday, O., Isiogu, N.C., 2024. Regenerative edible insects for food, feed, and sustainable livelihoods in Nigeria: consumption, potential and prospects. Future Foods. 9, 100309. https://doi.org/10.1016/j.fufo.2024.100309.

Alfiko, Y., Xie, D., Astuti, R.T., Wong, J., Wang, L., 2022. Insects as a feed ingredient for fish culture: status and trends. Aquacult. Fisheries 7 (2), 166–178. https://doi.org/10.1016/j.aaf.2021.10.004.

Amoah, I., Cobbinah, J.C., Yeboah, J.A., Essiam, F.A., Lim, J.J., Tandoh, M.A., Rush, E., 2023. Edible insect powder for enrichment of bakery products – a review of nutritional, physical characteristics and acceptability of bakery products to consumers. Future Foods. 8, 100251. https://doi.org/10.1016/j.fufo.2023.100251.

Anagonou, G.H., Gandji, K., Salako, K.V., Houetohossou, A., Zannou, E.T., Mensah, G.A., Assogbadjo, A.E., Chadare, F.J., 2024. Socio-economic and cultural drivers of local perceptions and willingness to consume edible insects in Benin. Future Foods. 10, 100424. https://doi.org/10.1016/j.fufo.2024.100424.

Ayele, J., Tolemariam, T., Beyene, A., Tadese, D.A., Tamiru, M., 2021. Assessment of livestock feed supply and demand concerning livestock productivity in lalo kile district of Kellem Wollega zone, Western Ethiopia. Heliyon. 7 (10), e08177. https://doi.org/10.1016/j.heliyon.2021.e08177.

Benjamin, S., Spener, F., 2009. Conjugated linoleic acids as functional food: an insight into their health benefits. Nutr. Metab. 6, 1–13. https://doi.org/10.1186/1743-7075-6-36.

Bhatt, D.L., Budoff, M.J., Mason, R.P., 2020. A revolution in omega-3 fatty acid research. J. Am. Coll. Cardiol. 76 (18), 2098–2101. https://doi.org/10.1016/j.jacc.2020.09.005.

Bionaz, M., Vargas-Bello-Pérez, E., Busato, S., 2020. Advances in fatty acids nutrition in dairy cows: from gut to cells and effects on performance. J. Anim. Sci. Biotechnol. 11 (1), 1–36. https://doi.org/10.1186/s40104-020-00512-8.

Calder, P.C., 2015. Marine omega-3 fatty acids and inflammatory processes: effects, mechanisms and clinical relevance. Biochimica et Biophysica Acta - Mol. Cell Biol. Lipids 1851 (4), 469–484. https://doi.org/10.1016/j.bbalip.2014.08.010.

Candyrine, S.C.L., Jahromi, M.F., Ebrahimi, M., Liang, J.B., Goh, Y.M., Abdullah, N., 2017. In vitro rumen fermentation characteristics of goat and sheep supplemented with polyunsaturated fatty acids. Anim. Prod. Sci. 57 (8), 1607–1612. https://doi.org/10.1071/AN15684.

Cao, X., Xia, J., Zhou, Y., Wang, Y., Xia, H., Wang, S., Liao, W., Sun, G., 2022. The Effect of MUFA-rich food on lipid profile: a meta-analysis of randomized and controlled-feeding trials. Foods. 11 (13), 1982. https://doi.org/10.3390/foods11131982.

T.B. T.-T. R. of F. F. S. Chaves, H., Singh, R.B., Khan, S., Wilczynska, A., Takahashi, T., 2019. In: Singh, R.B., Watson, R.R., Takahashi, G.H. (Eds.), Chapter 14 - High Omega-6/Omega-3 Fatty Acid Ratio Diets and Risk of Noncommunicable Diseases: Is the Tissue, the Main Issue?. Academic Press, pp. 217–259. https://doi.org/10.1016/B978-0-12-813148-0.00014-1. T.B. T.-T. R. of F. F. S.

In F. B. T.-A. in F Choi, Y.-S., Lee, J.H., Kim, T.-K., Shin, D.-M., 2024. Chapter six - edible insects in food. In: Toldrá, N.R. (Ed.), Chapter six - edible insects in food. Advances in Food and Nutrition Research 108, 223–264. https://doi.org/10.1016/bs.afnr.2023.10.005.

Dobermann, D., Swift, J.A., Field, L.M., 2017. Opportunities and hurdles of edible insects for food and feed. Nutr. Bull. 42 (4), 293–308. https://doi.org/10.1111/nbu.12291.

Dyall, S.C., 2015. Long-chain omega-3 fatty acids and the brain: a review of the independent and shared effects of EPA, DPA and DHA. Front. Aging Neurosci. 7 (APR), 1–15. https://doi.org/10.3389/fnagi.2015.00052.

Elahi, U., Xu, C.C., Wang, J., Lin, J., Wu, S.G., Zhang, H.J., Qi, G.H., 2022. Insect meal as a feed ingredient for poultry. Anim. Biosci. 35 (2), 332–346. https://doi.org/10.5713/ab.21.0435.

Ewald, N., Vidakovic, A., Langeland, M., Kiessling, A., Sampels, S., Lalander, C., 2020. Fatty acid composition of black soldier fly larvae (*Hermetia illucens*) – Possibilities and limitations for modification through diet. Waste Manag. 102, 40–47. https://doi.org/10.1016/j.wasman.2019.10.014.

FAO, 2008. Fats and fatty acids in human nutrition. In: Proceedings of the Joint FAO/WHO Expert Consultation, 91. https://doi.org/10.1159/000228993.

FAO, 2021. Looking at edible insects from a food safety perspective. Looking at Edible Insects from a Food Safety Perspective. https://doi.org/10.4060/cb4094en.

Finke, M.D., 2013. Complete nutrient content of four species of commercially available feeder insects. Zoo Biol. 32 (1), 27–36. https://doi.org/10.1002/zoo.21246.

Fragkos, K.C., Tsagris, M., Frangos, C.C., 2014. Publication bias in meta-analysis: confidence intervals for Rosenthal's fail-safe number. Int. Sch. Res. Notices. 2014, 1–17. https://doi.org/10.1155/2014/825383.

Freeman, M., Hibbeln, J., Wisner, K., Mischoulon, D., Peet, M., Keck, P., Marangell, L., Richardson, A., Lake, J., Stoll, A., 2006. Omega3 fatty acids: evidence basis for treatment and future research in psychiatry. J. Clin. Psychiatry 67, 1954–1967. https://doi.org/10.4088/JCP.v67n1217.

Gómez-Cortés, P., Frutos, P., Mantecón, A.R., Juárez, M., De La Fuente, M.A., Hervás, G., 2008. Milk production, conjugated linoleic acid content, and in vitro ruminal fermentation in response to high levels of soybean oil in dairy ewe diet. J. Dairy Sci. 91 (4), 1560–1569. https://doi.org/10.3168/jds.2007-0722.

Georgescu, B., Boaru, A.M., Muntean, L., Sima, N., Struți, D.I., Păpuc, T.A., Georgescu, C., 2022. Modulating the fatty acid profiles of *Hermetia illucens* larvae fats by dietary enrichment with different oilseeds: a sustainable way for future use in feed and food. Insects. 13 (9). https://doi.org/10.3390/insects13090801 art. no. 801.

Girón, J.E.P., Restrepo, M.L.P., Fornaguera, J.E.C., 2016. Supplementation with corn oil and palm kernel oil to grazing cows: ruminal fermentation, milk yield, and fatty acid profile. Revista Brasileira de Zootecnia 45 (11), 693–703. https://doi.org/10.1590/S1806-92902016001100008.

Godde, C.M., Mason-D'Croz, D., Mayberry, D.E., Thornton, P.K., Herrero, M., 2021. Impacts of climate change on the livestock food supply chain; a review of the evidence. Glob. Food Sec. 28, 100488. https://doi.org/10.1016/j.gfs.2020.100488.

Halloran, A., Roos, N., Eilenberg, J., Cerutti, A., Bruun, S., 2016. Life cycle assessment of edible insects for food protein: a review. Agron. Sustain. Dev. 36 (4). https://doi.org/10.1007/s13593-016-0392-8.

Heckmann, L.-H., Andersen, J.L., Eilenberg, J., Fynbo, J., Miklos, R., Jensen, A.N., Nørgaard, J.V., Roos, N., 2019. A case report on inVALUABLE: insect value chain in a circular bioeconomy. J. Insects Food Feed 5 (1), 9–13. https://doi.org/10.3920/JIFF2018.0009.

Hedges, L.V., Olkin, I., 1985. Statistical methods for meta-analysis. J. Educ. Statis. 13 (1), 75. https://doi.org/10.2307/1164953.

Huang, G., Zhang, Y., Liu, F., Xiao, J., Huang, D., 2025. Fatty acid profile of insect oil and regulation mechanism as nutritious and functional oil: an integrative review. J. Food Comp. Anal. 137 (106809). https://doi.org/10.1016/j.jfca.2024.106809 art. no.

Irawan, A., Hidayat, C., Jayanegara, A., Ratriyanto, A., 2021. Essential oils as growth-promoting additives on performance, nutrient digestibility, cecal microbes, and serum metabolites of broiler chickens: a meta-analysis. Anim. Biosci. 34 (9), 1499–1513. https://doi.org/10.5713/AB.20.0668.

Jalc, D., Potkanski, A., Szumacher-Strabel, M., Cieslak, A., Certik, M., 2005. Effect of microbial oil, evening primrose oil and borage oil on rumen fermentation in vitro. Vet. Med. (Praha) 50 (11), 480–486. https://doi.org/10.17221/5652-VETMED.

Jayanegara, A., Yantina, N., Novandri, B., Laconi, E.B., Nahrowi, Ridla, M, 2017. Evaluation of some insects as potential feed ingredients for ruminants: chemical composition, in vitro rumen fermentation and methane emissions. J. Indonesian Trop. Animal Agricult. 42 (4), 247–254. https://doi.org/10.14710/jitaa.42.4.247-254.

Jayanegara, A., Gustanti, R., Ridwan, R., Widyastuti, Y., 2020. Fatty acid profiles of some insect oils and their effects on in vitro bovine rumen fermentation and methanogenesis. Ital. J. Anim. Sci. 19 (1), 1311–1318. https://doi.org/10.1080/1828051X.2020.1841571.

Koricheva, J., Gurevitch, J., Mengersen, K., 2013. Handbook of Meta-Analysis in Ecology and Evolution. Princeton University Press.

Kouba, M., Mourot, J., 2011. A review of nutritional effects on fat composition of animal products with special emphasis on n-3 polyunsaturated fatty acids. Biochimie 93 (1), 13–17. https://doi.org/10.1016/j.biochi.2010.02.027.

Labu, S., Subramanian, S., Cheseto, X., Akite, P., Kasangaki, P., Chemurot, M., Tanga, C. M., Salifu, D., Egonyu, J.P., 2022. Agrochemical contaminants in six species of edible insects from Uganda and Kenya. Curr. Res. Insect Sci. 2, 100049. https://doi.org/10.1016/j.cris.2022.100049.

Liceaga, A.M., 2021. Processing insects for use in the food and feed industry. Curr. Opin. Insect Sci. 48, 32–36. https://doi.org/10.1016/j.cois.2021.08.002.

Liland, N.S., Araujo, P., Xu, X.X., Lock, E.J., Radhakrishnan, G., Prabhu, A.J.P., Belghit, I., 2021. A meta-analysis on the nutritional value of insects in aquafeeds. J. Insects Food Feed 7 (5), 743–759. https://doi.org/10.3920/JIFF2020.0147.

Makkar, H.P.S., Tran, G., Heuzé, V., Ankers, P., 2014. State-of-the-art on use of insects as animal feed. Anim. Feed Sci. Technol. 197, 1–33. https://doi.org/10.1016/j.anifeedsci.2014.07.008.

Meneguz, M., Schiavone, A., Gai, F., Dama, A., Lussiana, C., Renna, M., Gasco, L., 2018. Effect of rearing substrate on growth performance, waste reduction efficiency and chemical composition of black soldier fly (*Hermetia illucens*) larvae. J. Sci. Food Agric. 98 (15), 5776–5784. https://doi.org/10.1002/jsfa.9127.

Mozaffarian, D., Wu, J.H.Y., 2011. Omega-3 fatty acids and cardiovascular disease: effects on risk factors, molecular pathways, and clinical events. J. Am. Coll. Cardiol. 58 (20), 2047–2067. https://doi.org/10.1016/j.jacc.2011.06.063.

Muktiani, A., Arifah, N., Widiyanto, W., 2020. Influence of Different Vegetable Oils on In Vitro Ruminal Fermentability and Nutrient Digestibility in Ettawah Crossbred Goat. Anim. Prod. 21 (1), 22. https://doi.org/10.20884/1.jap.2019.21.1.689.

Nasir, S.Q., Świąder, K., 2022. Insects as food - opportunities and constraints. Technol. Progress Food Process. 2, 137–154. https://doi.org/10.31548/zemleustriy2022.02.

Nasir, S.Q., Palupi, E., Nasution, Z., Ploeger, A., Susanto, I., Setiawan, B., Rimbawan, R., Jayanegara, A., 2024. Edible insects as a sustainable protein source: a meta-analysis. J. Insects Food Feed 4588, 1–13. https://doi.org/10.1163/23524588-20230108.

NIH [National Institutes of Health]. 2022. Omega-3 fatty acids - fact sheet for health professionals. Office of Dietary Supplements. https://ods.od.nih.gov/factsheets/Omega3FattyAcids-HealthProfessional/#en.

Niyonsaba, H.H., Höhler, J., Kooistra, J., Van der Fels-Klerx, H.J., Meuwissen, M.P.M., 2021. Profitability of insect farms. J. Insects Food Feed 7 (5), 923–934. https://doi.org/10.3920/JIFF2020.0087.

Noosen, P., Lounglawan, P., Suksombat, W., 2017. Linseed oil supplemented concentrate fed to brahman crossbred fattening steers on carcass quality traits and intramuscular fatty acid profiles. Songklanakarin J. Sci. Technol. 39 (1), 1–10. https://doi.org/10.14456/sjst-psu.2017.1.

Oonincx, D.G.A.B., de Boer, I.J.M., 2012. Environmental Impact of the Production of Mealworms as a Protein Source for Humans - A Life Cycle Assessment. PLoS. One 7 (12). https://doi.org/10.1371/journal.pone.0051145.

Orkusz, A., 2021. Edible insects versus meat — Nutritional comparison: knowledge of their composition is the key to good health. Nutrients. 13 (1207). https://doi.org/10.3390/nu13041207.

Palupi, E., Jayanegara, A., Ploeger, A., Kahl, J., 2012. Comparison of nutritional quality between conventional and organic dairy products: a meta-analysis. J. Sci. Food Agric. 92 (14), 2774–2781. https://doi.org/10.1002/jsfa.5639.

Palupi, E., Anwar, F., Tanziha, I., Gunawan, M.A., Khomsan, A., Kurniawati, F., Muslich, M., 2020. Protein sources diversity from gunungkidul district, Yogyakarta province, Indonesia. Biodiversitas 21 (2), 799–813. https://doi.org/10.13057/biodiv/d210248.

Pereira, A.M., de Lurdes Nunes Enes Dapkevicius, M., Borba, A.E.S., 2022. Alternative pathways for hydrogen sink originated from the ruminal fermentation of carbohydrates: which microorganisms are involved in lowering methane emission? Anim. Microbiome 4 (1), 1–12. https://doi.org/10.1186/s42523-021-00153-w.

Perez-Santaescolastica, C., de Pril, I., van de Voorde, I., Fraeye, I., 2023. Fatty acid and amino acid profiles of seven edible insects: focus on lipid class composition and protein conversion factors. Foods. 12 (22), 4090. https://doi.org/10.3390/foods12224090.

Prachumchai, R., Cherdthong, A., 2023. Black Soldier Fly Larva Oil in Diets with Roughage to Concentrate Ratios on Fermentation Characteristics, Degradability, and Methane Generation. Animals 13 (15), 1–14. https://doi.org/10.3390/ani13152416.

Preyer, C., Davidowitz, G., 2021. Editorial overview: the time is ripe for expanded research on mass production of insects as food and feed. Curr. Opin. Insect Sci. 48, viii–vixi. https://doi.org/10.1016/j.cois.2021.11.003.

Rosenthal, R., 1979. The file drawer problem and tolerance for null results. Psychol. Bull. 86 (3), 638–641. https://doi.org/10.1037/0033-2909.86.3.638.

Rossi, G., Mattioli, S., Rondoni, G., Bosco, A.D., Servili, M., Castellini, C., Conti, E., 2022. Characterisation of fatty acid profiles of *Tenebrio molitor* larvae reared on diets enriched with edible oils. J. Insects Food Feed 8 (8), 901–912. https://doi.org/10.3920/JIFF2021.0164.

Rumpold, B.A., Schlüter, O.K., 2013. Nutritional composition and safety aspects of edible insects. Mol. Nutr. Food Res. 57 (5), 802–823. https://doi.org/10.1002/mnfr.201200735.

Schwingshackl, L., Zähringer, J., Beyerbach, J., Werner, S.S., Nagavci, B., Heseker, H., Koletzko, B., Meerpohl, J.J., 2021. A scoping review of current guidelines on dietary fat and fat quality. Ann. Nutrit. Metabol. 77 (65–82). https://doi.org/10.1159/000515671.

Siddiqui, S.A., Snoeck, E.R., Tello, A., Alles, M.C., Fernando, I., Saraswati, Y.R., Rahayu, T., Grover, R., Ullah, M.I., Ristow, B., Nagdalian, A.A., 2022. Manipulation of the black soldier fly larvae (*Hermetia illucens*; Diptera: stratiomyidae) fatty acid profile through the substrate. J. Insects Food Feed 8 (8), 837–855. https://doi.org/10.3920/JIFF2021.0162.

Siddiqui, S.A., Mahanta, D.K., Bhoi, T.K., Ahmad, A., Fernando, I., 2024. Mopane worm (*Gonimbrasia belina*)—An exclusive African edible insect as human food—A comprehensive review. Future Foods. 10, 100438. https://doi.org/10.1016/j.fufo.2024.100438.

Simopoulos, A.P., 2002. The importance of the ratio of Omega-6/Omega-3 essential fatty acids. Biomed. Pharmacotherapy 56 (8), 365–379. https://doi.org/10.1016/S0753-3322(02)00253-6.

Simopoulos, A.P., 2016. An increase in the Omega-6/Omega-3 fatty acid ratio increases the risk for obesity. Nutrients. 8 (3), 1–17. https://doi.org/10.3390/nu8030128.

Sogari, G., Amato, M., Biasato, I., Chiesa, S., Gasco, L., 2019. The potential role of insects as feed: a multi-perspective review. Animals 9 (4), 119. https://doi.org/10.3390/ani9040119.

Spake, R., Doncaster, C.P., 2017. Use of meta-analysis in forest biodiversity research: key challenges and considerations. For. Ecol. Manage. 400, 429–437. https://doi.org/10.1016/j.foreco.2017.05.059.

St-Pierre, N.R., 2001. Invited review. Integrating quantitative findings from multiple studies using mixed model methodology. J. Dairy Sci. 84 (4), 741–755. https://doi.org/10.3168/jds.S0022-0302(01)74530-4.

Stillwell, W., Wassall, S.R., 2003. Docosahexaenoic acid: membrane properties of a unique fatty acid. Chem. Phys. Lipids 126 (1), 1–27. https://doi.org/10.1016/S0009-3084(03)00101-4.

Sudarman, A., Muttakin, M., Nuraini, H., 2008. Penambahan sabun-kalsium dari minyak ikan lemuru dalam ransum: 2 pengaruhnya terhadap sifat kimia dan fisik daging domba. Jurnal Ilmu Ternak Dan Veteriner 19 (3), 133–139.

Sun, G.Y., Simonyi, A., Fritsche, K.L., Chuang, D.Y., Hannink, M., Gu, Z., Greenlief, C.M., Yao, J.K., Lee, J.C., Beversdorf, D.Q., 2018. Docosahexaenoic acid (DHA): an essential nutrient and a nutraceutical for brain health and diseases. Prostaglandins, Leukotrienes Essential Fatty Acids 136, 3–13. https://doi.org/10.1016/j.plefa.2017.03.006.

Susanto, I., Wiryawan, K.G., Suharti, S., Retnani, Y., Zahera, R., Jayanegara, A., 2023. Evaluation of Megasphaera elsdenii supplementation on rumen fermentation, production performance, carcass traits and health of ruminants: a meta-analysis. Anim. Biosci. 36 (6), 879–890. https://doi.org/10.5713/ab.22.0258.

Tanga, C.M., Egonyu, J.P., Beesigamukama, D., Niassy, S., Kimathi, E., Magara, H.J.O., Omuse, E.R., Subramanian, S., Ekesi, S., 2021. Edible insect farming as an emerging and profitable enterprise in East Africa. Curr. Opin. Insect Sci. 48, 64–71. https://doi.org/10.1016/j.cois.2021.09.007.

Tavendale, M.H., Meagher, L.P., Pacheco, D., Walker, N., Attwood, G.T., Sivakumaran, S., 2005. Methane production from in vitro rumen incubations with Lotus pedunculatus and Medicago sativa, and effects of extractable condensed tannin fractions on methanogenesis. Anim. Feed Sci. Technol. 123-124, 403–419. https://doi.org/10.1016/j.anifeedsci.2005.04.037. *Pa*.

Thirumalaisamy, G., Malik, P.K., Kolte, A.P., Bhatta, R., 2020. In vitro evaluation of graded level of Silkworm pupae (*Bombyx mori*) oil on methane production, fermentation characteristics, and protozoal populations. Vet. World 13 (3), 586–592. https://doi.org/10.14202/vetworld.2020.586-592.

van Huis, A., Van Itterbeeck, J., Klunder, H., Mertens, E., Halloran, A., Muir, G., Vantomme, P., 2013. Edible Insects: future Prospects for Food and Feed Security. Food Agricult. Org. United Nations 97 (18). Issue. https://library.wur.nl/WebQuery/wurpubs/fulltext/258042.

van Huis, A., 2015. Edible insects contributing to food security? Agricult. Food Secur. 4 (1). https://doi.org/10.1186/s40066-015-0041-5.

van Huis, A., 2020. Insects as food and feed, a new emerging agricultural sector: a review. J. Insects Food Feed 6 (1), 27–44. https://doi.org/10.3920/JIFF2019.0017.

von Schacky, C., 2021. Importance of epa and dha blood levels in brain structure and function. Nutrients. 13 (4). https://doi.org/10.3390/nu13041074.

Yen, A.L., 2015. Conservation of Lepidoptera used as human food and medicine. Curr. Opin. Insect Sci. 12, 102–108. https://doi.org/10.1016/j.cois.2015.11.003.