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RESEARCH ARTICLE

Effects of insect meals on fish digestibility, blood parameters, and economic performance: a meta-analysis

M.A. Aaqillah-Amr[1], *A. Hidir*[2], *M. Ikhwanuddin*[2], *N.A. Fatan*[1], *R. Muhammad-Rahimi*[1], *S. Ning-Shahira*[1], *R.G.N. Siankhe*[3], *G.W. Vandenberg*[4*], *C.M. Tanga*[5] *and R. Yossa*[1*]

[1]WorldFish, Jalan Batu Maung, 11960 Bayan Lepas, Penang, Malaysia; [2]Institute of Tropical Aquaculture and Fisheries, Universiti Malaysia Terengganu, 21030 Kuala Terengganu, Terengganu, Malaysia; [3]AquExperts International Inc., 306 River Landing Ave, Ottawa, ON K2J 3V4, Canada; [4]Département des sciences animales, Université Laval, Québec, QC G1V 0A6, Canada; [5]International Centre of Insect Physiology and Ecology (ICIPE), P.O. Box 30772-00100 Nairobi, Kenya; *grant.vandenberg@fsaa.ulaval.ca; r.yossa@cgiar.org

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Abstract

This review examines the use of insect meal (IM) as a substitute for fishmeal (FM) in fish feeds within the past decade. While global interest in this alternative is growing, research on its effects on fish digestibility, blood parameters, and economic performance has been limited. Meta-analysis on the apparent digestibility coefficient revealed a negative effect summary on dry matter (−0.92) and crude lipid (−0.51), although the difference between the two groups was relatively minor. However, a positive effect summary was reported in the apparent digestibility of crude protein (0.12), suggesting a potential advantage in the utilization of protein by fish fed with IM-containing diets. Whereas meta-analysis on fish blood parameters demonstrates varying effects summary, necessitating further research. Analysis of economic performance revealed an overall better economic performance in the IM diet with an effect summary of −0.08 for feed cost and 0.00 for the economic profit index. Overall use of IM in aquafeed shows promise in improving feed quality and fish performance, potentially becoming a sustainable alternative to traditional FM. Recommendations include exploring IM's impact on fish blood parameters through more investigations. Shifting focus from traditional measures to markers directly linked with fish health and immune response can provide more precise insights. Moreover, exploring various components of IM, such as lipids and functional elements like chitin, through simplified breakdown methods, can significantly enhance our comprehension of their nutritional value. Analyzing how each part influences fish health could pave the way for a sustainable and efficient alternative to FM in aquaculture.

Keywords

aquafeed – blood parameters – economic performance – fish digestibility – insect meal – meta-analysis

1 Introduction

Aquaculture, with its emphasis on responsible and efficient fish farming, has been exploring diverse alternatives to fishmeal (FM) to enhance sustainability and economic viability. At the same time, the emergence of insect meal (IM) has sparked considerable interest as a revolutionary alternative to FM in aquacul-

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ture. Its introduction in aquaculture signifies a remarkable shift in sustainable protein sources for aquatic species. The use of IM from seven insect species in aquafeeds has been identified in Europe following the approval granted by the European Union in 2017 (European Commission, 2017). This includes the black soldier fly (BSF) (*Hermetia illucens*), the common housefly (*Musca domestica*), the lesser mealworm (*Alphitobius diaperinus*), the yellow mealworm (*Tenebrio molitor*), the house cricket (*Acheta domesticus*), the banded cricket (*Gryllodes sigillatus*), and the field cricket (*Gryllus assimilis*). This novel protein source stands out for its high nutritional value, encompassing both macronutrients and micronutrients, mirroring the nutritional requirements vital for optimal growth and development in aquatic organisms (Nugroho and Nur, 2018; Salam *et al.*, 2021). Compared to traditional livestock or crop farming, insect farming offers major environmental advantages. These include requiring less land and water, exhibiting high feed conversion efficiencies, and having the unique ability to transform low-value organic by-products into high-quality frass (van Huis and Oonincx, 2017).

As most insects reproduce very quickly, within 30 to 50 days (Fernandez-Cassi *et al.*, 2019), the harvesting of insects can be done frequently. These insects have been widely farmed using several traditional methods, such as container farming (Morales-Ramos *et al.*, 2024), pit farming (Meutchieye *et al.*, 2016), and greenhouse farming (Coudron *et al.*, 2022). These methods involve raising insects in simple, excavated pits, or basic containers, making them suitable for home-scale or small-scale production. They are particularly beneficial in rural areas or for small-scale farmers, offering accessible entry points into insect farming. These approaches contribute to local food security and economic development by providing cost-effective and straightforward methods to produce high-nutrient biomass from organic waste. However, challenges such as maintaining optimal conditions for insect growth, including temperature, humidity, and hygiene, can be difficult in these methods. Additionally, they typically yield lower volumes compared to industrial methods, which may limit scalability. Despite these challenges, these farming methods hold significant potential such as empowering local communities, reducing dependence on imported feed, and promoting sustainable agricultural practices. By integrating traditional methods like pit farming with modern techniques and knowledge, productivity and efficiency in insect farming can be improved at various scales.

The interest in large-scale production of insects is now expanding to countries such as Malaysia (Nutrition Technologies; Entofood), China (Guangzhou Unique Biotechnology Co., Ltd., Inspro Science Ltd., Dingzhou Taigu Biotechnology Co., Ltd.), France (InnovaFeed, Ÿnsect), Singapore (Protenga, Insectta, Entobel), the United States (Beta Hatch), the UK (Entocycle), Canada (Entosystem), and the Netherlands (Protix) due to its low maintenance and space requirements (Smetana *et al.*, 2016; van Huis and Oonincx, 2017), with China leading. These insect culture industries use innovative techniques and technologies for large-scale production by employing a vertical insect production system integrated with automated machinery. This setup creates a zero-waste facility while maintaining high biosafety measures and top-notch quality standards. Among the farmed insects, the BSF and the yellow mealworm stand out for their ability to convert organic waste into high-nutrient biomass, rivaling FM (Henry *et al.*, 2015; Rema *et al.*, 2019). IM's use extends beyond aquaculture, finding applications in poultry and livestock farming (Elahi *et al.*, 2022; Sogari *et al.*, 2023; van Huis and Gasco, 2023).

However, debates persist regarding the use of IM in aquaculture, with consumer acceptance posing a significant challenge. Concerns about allergenicity to insect protein and hygienic practices arise, particularly when insects are farmed using waste materials (Wassman *et al.*, 2021). Despite the common consumption of insects in Asia, Africa, South America, and Oceania, integrating IM into the aquaculture industry as FM substitute requires time for consumer acceptance. Various sensory studies assessing fish fed diets with IM have unveiled noteworthy insights. For instance, assessments involving both trained and untrained sensory panels – regular consumers of fish – examined attributes like color, texture, flavor, appearance, and odor of fish meat or fillet (Lock *et al.*, 2015; Chaklader *et al.*, 2023; Bruni *et al.*, 2019, 2021). Fish-fed IM displayed paler flesh color compared to wild-caught fish, indicating lower fillet quality in the former, consequently affecting overall liking scores (Bruni *et al.*, 2019). Preferences for a firmer texture in fish meat, likely influenced by higher lipid content, were noted (Turek *et al.*, 2020). However, higher IM inclusion in diets resulted in lower scores for color intensity in cooked salmon (Belghit *et al.*, 2019), as well as changes in aroma, taste, and aftertaste in rainbow trout (Turek *et al.*, 2020). Conversely, attributes such as tenderness, juiciness, and fibrousness were deemed acceptable by consumers of fish with a high IM percentage (Bruni *et al.*, 2019, 2021). Notably, sensory panels in fillet testing often failed to discern significant differences between fish fed diets with FM and IM (Basto *et al.*, 2023a). This suggests that partial IM replacement might be preferable over total FM replacement, based on observed sensory attributes. In addition, studies have indicated that consumers are more likely to accept this innovation when processed rather than used in its original form (Chao *et al.*, 2018).

Moreover, concerns about the environmental impact of insect culture stem from claims suggesting increased energy consumption and a higher carbon footprint (Le Féon *et al.*, 2019). However, Tran *et al.* (2021) argued against these claims, attributing potential problems to arise possibly due to poor digestibility. Studies on IM in fish diets found that several insects are poorly digested due to high chitin levels when added in excessive amounts (Fontes *et al.*, 2019; Elesho *et al.*, 2021; Mastoraki *et al.*, 2020). These challenges underscore the necessity for comprehensive evaluations of IM impact on various fish parameters, encompassing fish digestibility and their effect on fish blood parameters. While several meta-analyses have assessed parameters like fish nutritional profile (Gougbedji *et al.*, 2022), growth performance (Hua, 2021; Luthada-Raswiswi *et al.*, 2021; Weththasinghe *et al.*, 2021; Gougbedji *et al.*, 2022; Prakoso *et al.*, 2022; Rapatsa and Moyo, 2022), feed efficiency (Rapatsa and Moyo, 2022), and consumer acceptance (Wassmann *et al.*, 2021) in response to FM substitution with IM, studies focusing on fish welfare and economic performance remain scarce. Given the relatively new adoption of IM as the main protein source in aquaculture feeds, conducting a meta-analysis on IM's effect on fish digestibility, blood parameters, and overall economic performance becomes imperative. Apparently, assessing blood parameters in fish is crucial because these metrics serve as reliable indicators of fish health and physiological status, reveal the impact of dietary changes on fish metabolism, immune response, and overall well-being (Ahmed *et al.*, 2020). Parameters such as hematocrit, blood cell counts, and various biochemical markers (i.e. total protein, triglycerides, glucose, and cholesterol) provide insights into how well fish can utilize IM and adapt to it as part of their diet. This information is vital for ensuring that IM does not negatively affect fish health, which is a critical aspect of sustainable aquaculture practices. Economic performance, on the other hand, directly influences its feasibility for widespread adoption by considering the cost of production, potential savings from using IM, and financial benefits from better growth rates and feed conversion ratios. Additionally, understanding the market dynamics and consumer willingness to pay for fish products raised on IM diets is essential for determining the economic viability of this alternative protein source. By examining these economic aspects, the research can provide a comprehensive assessment of the potential benefits and challenges associated with IM adoption in the aquaculture industry.

This article aims to provide an overview of recent advancements in developing fish feeds from diverse insect proteins and their impact on apparent digestibility coefficient (ADC), blood parameters, and economic analysis. These research areas are crucial for validating IM as a sustainable alternative to FM and supporting its integration into commercial aquaculture. Comprehensive data are essential for understanding the benefits of using IM as a partial or full FM replacement, offering valuable insights for the public and policymakers.

2 Materials and method

Literature search and data extraction to include in meta-analyses

A systematic literature search was conducted through electronic databases such as Google Scholar and Web of Science in August 2023, for published research over the last 10 years (2013 – August 2023), using a combination of search keywords (insect meal, aquafeed, digestibility, blood parameters, and feed cost). The first step started with a screening of each article's title and abstract initial search generated 5,530 articles (Figure 1). The literature search for meta-analyses eliminated review articles, surveys, conference proceedings, preprints, patents, thesis dissertations, and article-in-press. Articles reporting the incorporation of IM in poultry feed, and ornamental fish such as zebrafish, goldfish, and guppy were also excluded. Among these, 5,383 studies did not fit the criteria, leaving 147 articles to be included in the systematic review and 65 relevant articles for the meta-analysis.

Data screening was used to assess research direction, study types, types of insects used, and replacement of FM with IM (total or partial). This analysis aimed to track the progression of IM in aquaculture and combine experimental results to enhance future decision-making in aquaculture applications. The meta-analysis adhered to the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement principles. Predefined criteria for study inclusion in the meta-analysis database were applied separately, covering the effects of FM replacement with IM on (a) fish digestibility, (b) fish blood parameters, and (c) economic performance.

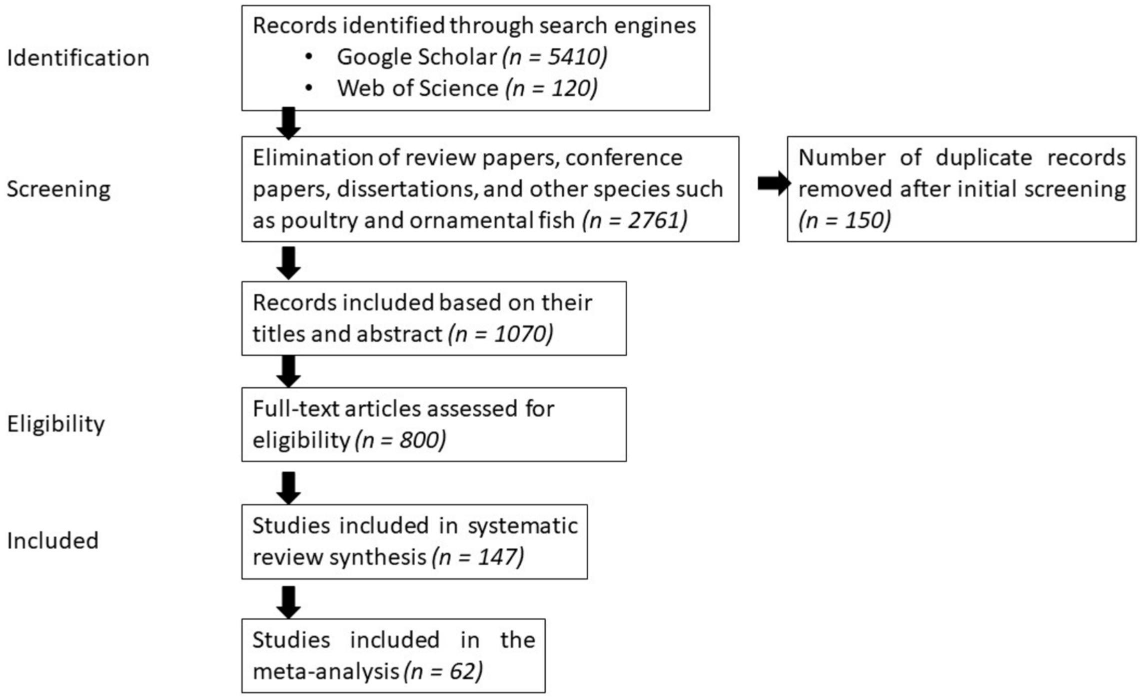

FIGURE 1 Summary of the selection process for the research articles included in the meta-analysis.

Specifically, 32 articles were used for digestibility, 42 articles for blood parameters, and 10 articles for economic analysis. Some studies provided data for multiple parameters, while others focused on a single aspect, resulting in overlapping counts. This ensures comprehensive coverage across different aspects of IM's impact on aquaculture.

We incorporated studies that offer insights into the impact of insects (e.g. BSF, superworm, mealworm, etc.) at different life stages (e.g. larvae, prepupae, and imago) and IM processing (e.g. full fat, defatted, partially defatted, etc.) in the diets of various fish species (e.g. sea bass, catfish, tilapia, etc.) at varying growth stages (e.g. larvae, fingerling, juvenile, and adult), and their feeding habits (omnivorous, carnivorous, and herbivorous). These studies also provide information on FM replacement (partial or total). The overview of studies included in the meta-analysis is presented in Table 1.

Statistical analysis

In this study, we calculated each study's effect size (Hedges' g) based on sample size, means, and standard deviations of control and treatment diets. A mixed model (fixed or random effect) was used, considering heterogeneity (Q) among studies. The between-study variance (or tau-squared, τ^2) was calculated to find to which extent the true effect sizes varied within the meta-analysis. A τ^2 of 0.00 indicated a fixed-effects model; otherwise, a random-effects model was used. After that, the calculated heterogeneity caused by true effects was computed using I^2 statistics (Higgins and Thompson, 2002; Higgins *et al.*, 2003). A chi-squared test (χ^2) was calculated for the heterogeneity test at $P < 0.05$.

The forest plot was designed based on each study's bias-corrected effect size and 95% confidence interval (CI95%) from each study. The vertical line signifies the line of no effect, denoting no clear difference between the IM group and the control group. The desired outcome (favoring the IM group) was located to the right of the vertical line. An exception was made for feed cost, where the favoring treatment group (IM group) has been positioned on the left to indicate a positive outcome associated with lower costs. The effect summary was calculated and drawn in the forest plot to conclude the analysis. All data analyses and forest plot designs were conducted in Microsoft Excel (Microsoft 365) following Neyeloff *et al.* (2012) and Lajeunesse (2021).

3 Results and discussion

Research direction

Figure 2 illustrates the research trajectory based on publications, showcasing the remarkable progression observed in the evaluation of IM as a substitute for FM over the past decade (2013 – August 2023). The timeline indicates that the utilization of IM as a replacement

TABLE 1 Overview of studies included in the meta-analysis (N = 65)

Author	IM	IM Stage	Fish species	Feeding habits stage	Fish growth	IM Processing	Replacement with FM
Wang *et al.* (2019)	BSF	Larvae *japonicus*)	Seabass (*Lateolabrax*	Carnivorous	Juvenile	Defatted	Partial
Abdel-Latif *et al.* (2021)	BSF	Larvae	Seabass (*Dicentrarchus labrax*)	Carnivorous	Juvenile	Full fat	Partial
Abdel-Tawwab *et al.* (2020)	BSF	Larvae	Seabass (*D. labrax*)	Carnivorous	Juvenile	Full fat	Partial
Basto *et al.* (2020)	Mealworm	Larvae	Seabass (*D. labrax*)	Carnivorous	Juvenile	Defatted	Partial
Basto *et al.* (2021)	Mealworm	Larvae	Seabass (*D. labrax*)	Carnivorous	Juvenile	Defatted	Partial
Basto *et al.* (2023a)	Mealworm	Larvae	Seabass (*D. labrax*)	Carnivorous	Juvenile	Defatted	Partial
Basto *et al.* (2023b)	Mealworm	Larvae	Seabass (*D. labrax*)	Carnivorous	Juvenile	Defatted	Partial
Gasco *et al.* (2016)	Mealworm	Larvae	Seabass (*D. labrax*)	Carnivorous	Juvenile	Full fat	Partial
Magalhães *et al.* (2017)	BSF	Prepupae	Seabass (*D. labrax*)	Carnivorous	Juvenile	Partially defatted	Partial
Mastoraki *et al.* (2020)	Various	Larvae	Seabass (*D. labrax*)	Carnivorous	Fingerling	Partially defatted	Partial
Adeoye *et al.* (2020)	BSF	Larvae	Catfish (*Clarias gariepinus*)	Carnivorous	Fingerling	Full fat	Partial
Anvo *et al.* (2017)	Caterpillar	Larvae	Catfish (*C. gariepinus*)	Carnivorous	Fingerling	Full fat	Partial
Kolawole *et al.* (2023)	Cockroach	Imago	Catfish hybrid	Carnivorous	Fingerling	Full fat	Total
*Alves *et al.* (2020)	Superworm	Larvae	Tilapia (*Oreochromis niloticus*)	Omnivorous	Juvenile	Full fat	Partial
Amer *et al.* (2021)	Leafworm	Imago	Tilapia (*O. niloticus*)	Omnivorous	Juvenile	Full fat	Partial
Cadena-Cadena *et al.* (2023)	Cricket	Imago	Tilapia (*O. niloticus*)	Omnivorous	Fingerling	Full fat	Partial
Ngalya *et al.* (2020)	Caterpillar	n/a	Tilapia (*O. niloticus*)	Omnivorous	Juvenile	Full fat	Partial
Tippayadara *et al.* (2021)	BSF	Larvae	Tilapia (*O. niloticus*)	Omnivorous	Fingerling	Full fat	Total
Wachira *et al.* (2021)	BSF	Larvae	Tilapia (*O. niloticus*)	Omnivorous	Fingerling	Full fat	Total
Somdare *et al.* (2023)	BSF	Larvae	Tilapia (*Oreochromis* sp.)	Omnivorous	Fry	Full fat	Partial
Belghit et al. (2019)	BSF	Larvae	Atlantic salmon (*Salmo salar*)	Carnivorous	Adult	Partially defatted	Total
Caimi *et al.* (2020)	BSF	Larvae	Sturgeon (*Acipenser baerii*)	Carnivorous	Juvenile	Defatted	Partial
Rawski *et al.* (2020)	BSF	Larvae	Sturgeon (*A. baerii*)	Carnivorous	Fingerling	Full fat	Partial
Rawski *et al.* (2021)	BSF	Larvae	Sturgeon (*A. baerii*)	Carnivorous	Fingerling	Full fat	Partial
Caimi *et al.* (2021)	BSF	Larvae	Rainbow trout (*Oncorhynchus mykiss*)	Carnivorous	Juvenile	Partially defatted	Partial
Cardinaletti *et al.* (2019)	BSF	Prepupae	Rainbow trout (*O. mykiss*)	Carnivorous	Juvenile	Full fat	Partial

TABLE 1 (Continued)

Author	IM	IM Stage	Fish species	Feeding habits stage	Fish growth	IM Processing	Replacement with FM
Chemello *et al.* (2020)	Mealworm	Larvae	Rainbow trout (*O. mykiss*)	Carnivorous	Juvenile	Partially defatted	Total
Dumas *et al.* (2018)	BSF	Larvae	Rainbow trout (*O. mykiss*)	Carnivorous	Juvenile	Partially defatted	Partial
Gasco *et al.* (2022)	Various	Larvae	Rainbow trout (*O. mykiss*)	Carnivorous	Juvenile	Defatted	Partial
Henry *et al.* (2018)	Mealworm	Larvae	Rainbow trout (*O. mykiss*)	Carnivorous	Juvenile	Full fat	Partial
Jeong *et al.* (2020)	Mealworm	Larvae	Rainbow trout (*O. mykiss*)	Carnivorous	Fry	Full fat	Partial
Melenchón *et al.* (2022)	Mealworm	Larvae	Rainbow trout (*O. mykiss*)	Carnivorous	Juvenile	Full fat	Partial
Melenchón *et al.* (2023)	Mealworm	n/a	Rainbow trout (*O. mykiss*)	Carnivorous	Juvenile	Full fat	Partial
Long *et al.* (2022)	Cockroach	Larvae	Rainbow trout (*O. mykiss*)	Carnivorous	Juvenile	Full fat	Partial
Prakash *et al.* (2023)	BSF	Larvae	Rainbow trout (*O. mykiss*)	Carnivorous	Juvenile	Full fat	Partial
Rema *et al.* (2019)	Mealworm	Larvae	Rainbow trout (*O. mykiss*)	Carnivorous	Juvenile	Defatted	Total
Renna *et al.* (2017)	BSF	Larvae	Rainbow trout (*O. mykiss*)	Carnivorous	Juvenile	Partially defatted	Partial
Shekarabi *et al.* (2021)	Superworm	Larvae	Rainbow trout (*O. mykiss*)	Carnivorous	Fingerling	Defatted	Partial
Vale Pereira *et al.* (2023)	BSF	n/a	Rainbow trout (*O. mykiss*)	Carnivorous	Juvenile	Full fat	Total
Terova *et al.* (2019)	BSF	Prepupae	Rainbow trout (*O. mykiss*)	Carnivorous	Juvenile	Partially defatted	Partial
Mikołajczak *et al.* (2020)	Various	Larvae	Sea trout (*Salmo trutta*)	Carnivorous	Fingerling	Hydrolysis	Partial
Chaklader *et al.* (2019)	BSF	Larvae	Barramundi (*Lates calcarifer*)	Carnivorous	Juvenile	Full fat	Partial
Hender *et al.* (2021)	BSF	Larvae	Barramundi (*L. calcarifer*)	Carnivorous	Juvenile	Partially defatted	Partial
Prachom *et al.* (2021)	Superworm	Larvae	Barramundi (*L. calcarifer*)	Carnivorous	Juvenile	Defatted	Partial
Di Rosa *et al.* (2023)	BSF	Larvae	Gilthead bream (*Sparus aurata*)	Omnivorous	Juvenile	Partially defatted	Partial
Fabrikov *et al.* (2021)	Various	Larvae	Gilthead bream (*S. aurata*)	Omnivorous	Juvenile	Full fat	Partial
Gai *et al.* (2023)	BSF	Larvae	Gilthead bream (*S. aurata*)	Omnivorous	Adult	Partially defatted	Partial
Henry *et al.* (2022)	Superworm	Larvae	Gilthead bream (*S. aurata*)	Omnivorous	Juvenile	Full fat	Partial
Piccolo *et al.* (2017)	Mealworm	Larvae	Gilthead bream (*S. aurata*)	Omnivorous	Juvenile	Full fat	Partial

TABLE 1 (Continued)

Author	IM	IM Stage	Fish species	Feeding habits stage	Fish growth	IM Processing	Replacement with FM
Tefal *et al.* (2023)	n/a	Larvae	Gilthead bream (*S. aurata*)	Omnivorous	Juvenile	Full fat	Total
Gebremichael *et al.* (2022)	Mealworm	n/a	Common carp (*Cyprinus carpio*)	Omnivorous	Juvenile	Defatted	Total
Ghosh and Mandal (2019)	Grasshopper	Imago	Rohu (*Labeo rohita*)	Herbivorous	Fingerling	De-chitin	Partial
Guerreiro *et al.* (2020)	BSF	Larvae	Meagre (*Argyrosomus regius*)	Carnivorous	Juvenile	Partially defatted	Partial
Nyuliwe *et al.* (2022)	Mopane worm	Larvae	Kob (*Argyrosomus japonicus*)	Carnivorous	Fingerling	Degutted	Partial
Hu *et al.* (2020)	BSF	Larvae	Rice field eel (*Monopterus albus*)	Carnivorous	Juvenile	Full fat	Partial
*Hu *et al.* (2023)	BSF	Larvae	Grass carp (*Ctenopharyngodon idellus*)	Herbivorous	Adult	Partially defatted	Total
*Li *et al.* (2023)	Mealworm	n/a	Grass carp (*C. idellus*)	Herbivorous	Adult	Full fat	Total
Lu *et al.* (2020)	BSF	Larvae	Grass carp (*C. idellus*)	Herbivorous	Juvenile	Defatted	Partial
Jeong *et al.* (2021a)	Cricket	n/a	Olive flounder (*Paralichthys olivaceus*)	Carnivorous	Juvenile	Full fat	Partial
Jeong *et al.* (2021b)	Mealworm	n/a	Olive flounder (*P. olivaceus*)	Carnivorous	Juvenile	Defatted	Partial
*Monteiro dos Santos et al. (2023)	BSF	Larvae	Tambaqui (*Colossoma macropomum*)	Herbivorous	Juvenile	Full fat	Partial
Ordoñez *et al.* (2022)	BSF	Larvae	Tambaqui (*C. macropomum*)	Herbivorous	Juvenile	Full fat	Partial
Prachom *et al.* (2023)	Cricket	Imago	Snakehead (*Channa striata*)	Carnivorous	Juvenile	Full fat	Total
Stejskal *et al.* (2020)	BSF	Larvae	Perch (*Perca fluviatilis*)	Carnivorous	Juvenile	Partially defatted	Partial
Stejskal *et al.* (2023)	BSF	Larvae	Perch (*P. fluviatilis*)	Carnivorous	Juvenile	Defatted	Partial

*Study was used to replace SBM instead of FM. BSF = Black soldier fly; IM = insect meal; n/a = not available; SBM = soybean meal.

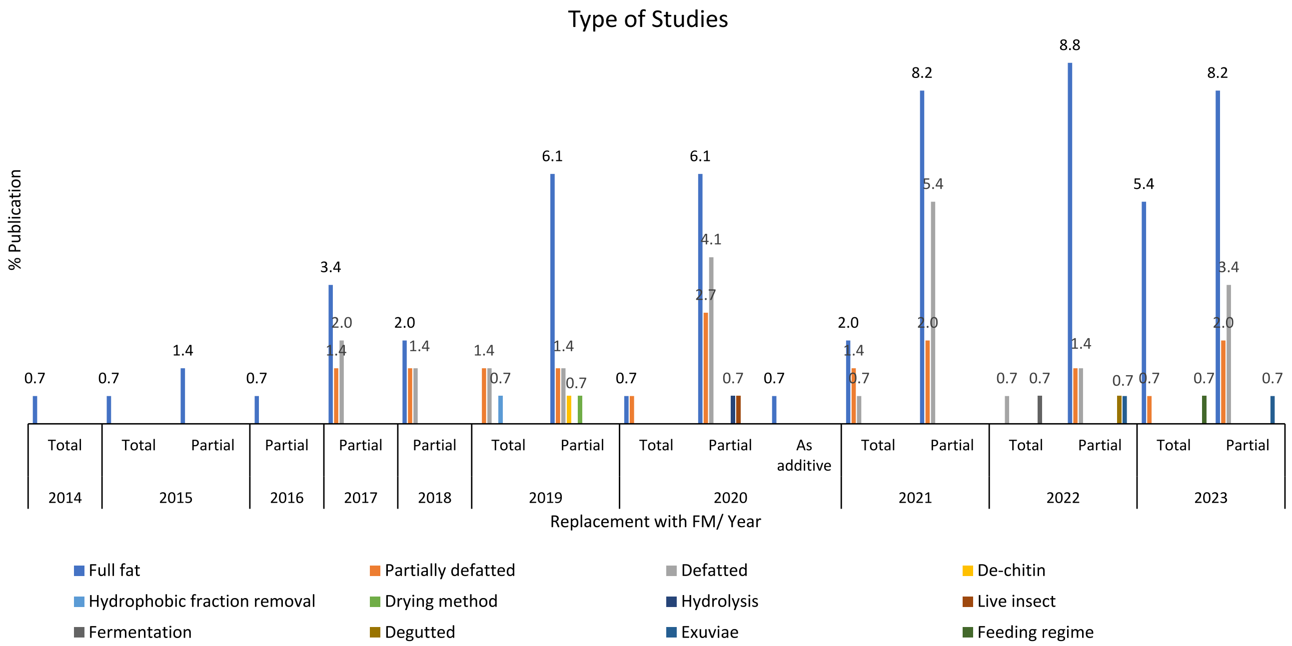

FIGURE 2 Research direction based on publications on insect-based aquafeeds from 2013 – August 2023 (N = 147).

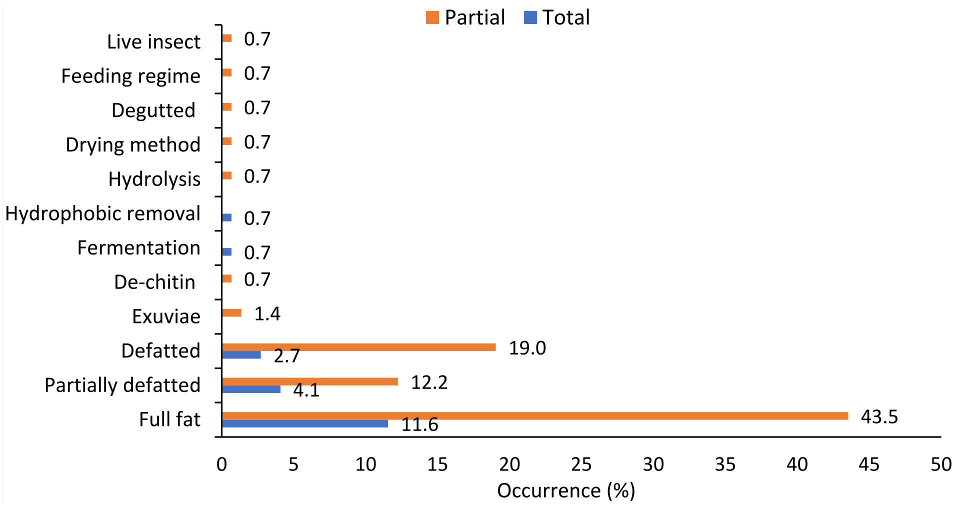

FIGURE 3 Percentage (%) occurrence of insect-based aquafeed substitution for fishmeal in different study types (N = 147).

for FM commenced in 2014, with an initial experiment involving the complete substitution of FM with full-fat IM (0.7%). Subsequently, in 2015, research endeavors diversified to encompass various approaches. Notably, there was a transition towards gradual replacements of FM with full-fat IM, constituting 1.4% of the studies, while the total replacement of FM with IM remained at 0.7%. The period from 2016 to 2018 witnessed a predominant concentration of the partial replacement of FM with IM, contributing 0.7%, 6.8%, and 4.8% in the years 2016, 2017, and 2018, respectively. Concurrently, the years 2017 and 2018 marked a surge in efforts aimed at enhancing the quality of IM, reflected in studies focusing on processes such as defatting and partial defatting of IM in fish feed. Starting from 2019 onward, the research landscape exhibited greater diversification in investigations into the partial and total replacement of FM with IM. Noteworthy advancements included explorations into defatting, de-chitinization, hydrophobic fraction removal, degutting, fermentation, drying methodologies of IM, utilization of exuviae, implementation of specific feeding regimes, and even direct feeding of live insects to fish.

Figure 3 outlines the distribution of publications across diverse study types. Out of the N = 147 studies, full-fat IM (55.1%) shows a clear preference, with 11.6% using it for total FM replacement and 43.5% for partial FM replacement. Notably, full-fat IM is widely favored due to its practicality and potential cost savings during processing. Nevertheless, its high lipid content creates challenges during feed extrusion, impacting feed durability and water stability (Weththasinghe *et al.*, 2021), while also leading to lipid oxidation and subsequent rancidity, thereby affecting both feed quality and fish palatability (Chaklader *et al.*, 2022). Moreover, the imbalanced fatty acid profile, with an elevated saturated fatty acid content, can lead to lipid accumulation in fish livers (Zarantoniello *et al.*, 2023). Given the higher lipid content found in IM, such as 20% in cricket (Prachom *et al.*, 2023), 36% in BSF (Tippayadara *et al.*, 2021), and 29% in yellow mealworm (Basto *et al.*, 2020), which surpasses the 10% lipid content of FM (Caimi *et al.*, 2020), the partial replacement strategy appears to be a more viable option. This trend is reflected in the study preferences which employed partial replacement of full-fat IM with FM compared to the total FM replacement. This approach could maintain optimal lipid levels in fish diets while mitigating lipid oxidation and preserving the feed's physical structure. Following this, the defatted IM in fish diets garnered 21.7% occurrence (2.7% for total and 19.0% for partial FM replacement), while partially defatted IM constituted 16.3% occurrence (4.1% for total and 12.2% for partial FM replacement). The defatted IM offers benefits in terms of feed efficiency and fish performance. This is due to its higher protein content (50.6% crude protein) and lower lipid content (8.2% crude lipid) as reported in BSF compared to full-fat IM (Karapanagiotidis *et al.*, 2023). Referring to Figure 3, most of the research appeared to prefer the use of defatted IM at a partial FM replacement over the total FM replacement. Considering the lack of EPA and DHA in IM (Fabrikov *et al.*, 2021), the total replacement of FM with IM could diminish fish performance due to the lack of essential nutrients. However, through partial replacement, integrating FM into the diet helps maintain a balanced intake, addressing these deficiencies and potentially bolstering overall fish health and performance. Based on the information presented, it appears that partial replacement of FM with IM could offer a more efficient strategy, as opposed to the labor-intensive process of defatting IM.

Other investigated areas, such as de-chitinization, hydrophobic fraction removal, drying methods, live insects, degutted approaches, and fermentation, each constituted 0.7% of the total publications (Figure 3). The presence of chitin, a major component of insect exoskeletons, seemingly impedes the use of IM in aquafeed, as noted by Gasco *et al.* (2019), limiting its potential benefits. However, the scarcity of studies focused on removing chitin from IM suggests that its presence may not significantly affect fish performance when partially replacing FM. This area requires further in-depth studies to achieve a more comprehensive understanding. Despite this limitation, Su *et al.* (2017) reported an interesting outcome – introducing de-chitinized mealworms into the yellow catfish's diet, replacing 50% of IM with FM resulting in an enhanced immune response against infections and diseases. Similarly, Ghosh and Mandal (2019) demonstrated that by removing grasshopper appendages to reduce excess chitin and replacing 50% of FM in the rohu diet, growth performance comparable to traditional FM-based diets was maintained. These methods have been successfully validated, particularly in shrimp meals, which are extensively incorporated as primary protein sources in aquafeed alongside FM (Rimoldi *et al.*, 2023). Effective removal techniques for chitin in shrimp meals imply potential solutions for challenges with IM, potentially making it a viable and common feed ingredient in the future. On the other hand, Fontes *et al.* (2019) noted that chitin content in IM did not appear to affect the lipid digestibility of tilapia fingerlings. These observations suggest that different fish species may exhibit varying levels of tolerance to chitin, which might be related to fish feeding behaviors, whether herbivorous, omnivorous, or carnivorous. Table 1 shows the type of IM used in fish diets based on their feeding behaviors. Considering species-specific dietary needs, carnivorous fish typically require high protein and essential fatty acids, making full-fat IM from species such as BSF suitable as a FM replacement totally or partially (Cardinaletti *et al.*, 2019; Caimi *et al.*, 2020; Caimi *et al.*, 2021). In contrast, herbivorous fish typically require lower protein levels and higher fiber in their diets, traditionally met by plant-based proteins such as soybean meal (SBM). The use of IM offers an alternative protein source that can contribute to a balanced diet, providing essential amino acids and nutrients crucial for growth and health. Studies in Table 1 show instances where IM partially or fully replaces SBM or FM in herbivorous fish diets (Hu *et al.*, 2023; Li *et al.*, 2023; Ghosh and Mandal, 2019; Lu *et al.*, 2020), highlighting the importance of nutritional requirements and feed formulation goals in choosing suitable IM types (full fat, defatted, partially defatted, de-chitinized). Considering this, partially defatted IM may be more appropriate for herbivorous fish due to its balanced nutrient profile with reduced fat content but essential amino acids and micronutrients intact. Omnivorous fish, with their flexible dietary requirements, can benefit from both full-fat and defatted IM, depending on specific nutritional targets in their diet formulation. Cadena-Cadena *et al.* (2023) mentioned

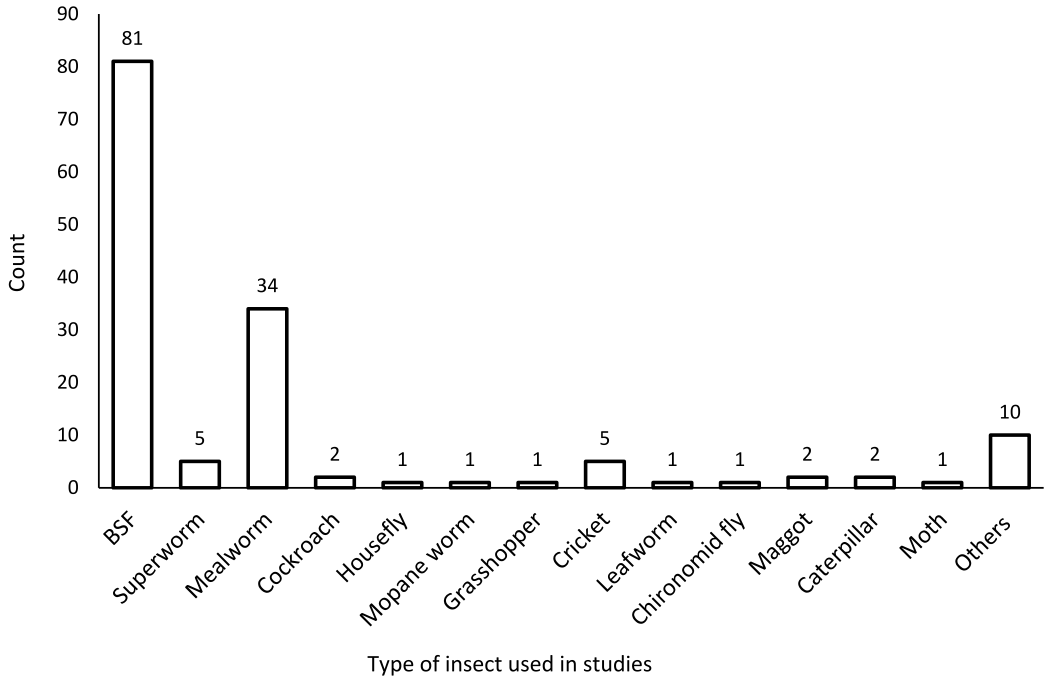

FIGURE 4 Type of insect used in the studies (N = 147).

Nile tilapia, being omnivorous has high resistance and adaptability to different types of food. However, these feeding preferences do not necessarily dictate the selection of IM types such as full fat, defatted, or partially defatted. Instead, the choice of IM type is primarily driven by the specific nutritional requirements of each fish species and the desired formulation of their diet.

Therefore, while feeding habits provide a framework for understanding fish species' nutritional needs, the selection of IM type is driven by the nutritional composition of the IM and how well it meets the specific dietary requirements of the targeted fish species. Figure 4 shows the distribution of insect species used in the study. BSF is the most frequently utilized species, with 81 studies, followed by mealworm with 34 studies. Superworm and cricket are both used 5 times each. Other species such as cockroach, housefly, mopane worm, short-horned grasshopper, leafworm, chironomid fly, maggot, caterpillar, and moth are used less frequently, each contributing fewer than 5 studies. The high frequency of BSF and yellow mealworm use in most studies suggests that they are widely recognized for their favorable nutrient profile and practical advantages in feed production. Its high protein content, coupled with manageable lipid levels makes them a preferred choice for researchers seeking sustainable alternatives to traditional FM. Furthermore, the life stage of insects significantly affects their nutrient composition. IM derived from larval stages has been found to contain lower lipid content (<20%) (Abdel-Latif *et al.*, 2021) compared to meal obtained from prepupae and imago stages (>30%) (Cardinaletti *et al.*, 2019; Mohd-Yusoff *et al.*, 2022) in the case of BSF. Consequently, researchers opted for IM sourced from larvae stages, known for their lower lipid and chitin levels compared to prepupae and imago stages. This preference aligns with evidence from Figure 5, highlighting that studies focusing on larvae stage IM are more prevalent than those involving prepupae or adult insects. Among these studies, full-fat insects were used in the majority (43.64%), followed closely by partially defatted and defatted ones at 21.82% each. The difference in lipid content between insect life stages presents practical challenges, necessitating researchers to consider not only nutritional disparities but also the feasibility of handling various consistencies of IM in feed production. This disparity suggests that larval-derived meal is more manageable for practical handling. The drier nature of larval-derived meals makes it more operationally feasible for existing storage, transport, and mixing equipment in feed production.

Meta-analyses

Fish digestibility

The meta-analyses examining the ADC of dry matter, crude protein, and crude lipid are summarized in Table 2, while their respective forest plots are depicted in Figure 6. In general, the ADC of nutrients is a crucial measure of nutrient utilization in fish. The analysis indicated a trend favoring the control group in the ADC, showing an overall effect summary of −0.92

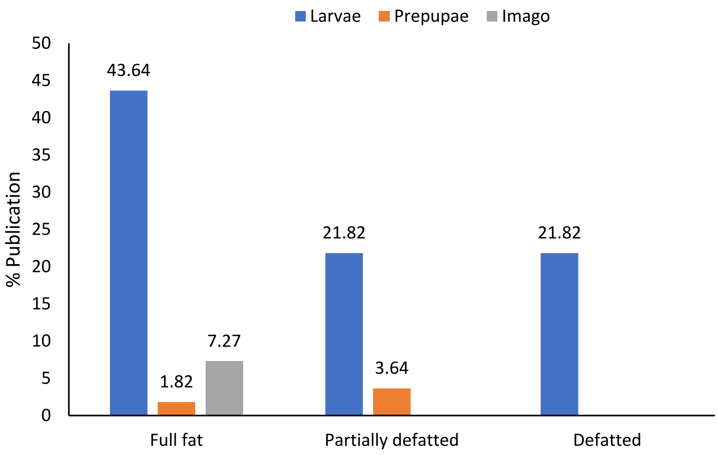

FIGURE 5 Publication of study types utilizing insect meal at different insect growth stage.

TABLE 2 Sub-data sets analysis comparing the effect of feeding insect meal on apparent digestibility, fish health, and economic sustainability of fish in aquaculture

Parameter	df	Mixed model (fixed or random effect) based on heterogeneity				Effect summary	CI95%
		τ^2	Q	p	I^2		
Apparent digestibility coefficient							
(i) Dry matter	19	3.88	62.61	0.00	69.65	−0.92	−1.97 to 0.14
(ii) Crude protein	27	5.25	77.46	0.00	65.14	0.12	−0.82 to 1.07
(iii) Crude lipid	21	2.72	37.85	0.01	44.51	−0.51	−1.33 to 0.31
Fish blood parameters							
(i) Non-specific immune							
- Lysozyme activity	15	12.05	126.35	0.00	88.13	2.38	0.40 to 4.37
(ii) Blood metabolite							
- Glucose	21	1.99	4.80	1.00	−337.60	0.31	−0.38 to 1.00
- Total protein	15	4.846	8.94	0.88	726.13	−1.36	−2.52 to −0.20
- Triglycerides	17	5.16	76.61	0.00	77.81	0.84	−0.34 to 2.02
- Cholesterol	23	4.04	92.68	0.00	75.18	−0.46	−1.38 to 0.45
(iii) Hematological							
- Hemotocrit	7	10.36	0.81	1.00	−762.11	0.31	−1.99 to 2.60
- Monocytes	7	0.48	13.17	0.07	46.84	−0.02	−0.72 to 0.69
Economic analysis							
(i) Fish feed cost	9	0.00	6.93	0.64	−29.86	−0.07*	−0.31 to 0.15
(ii) Economic profit index	5	0.00	4.39	0.50	−14.02	0.00	−0.47 to 0.49

*The negative effect summary for feed cost indicates a positive outcome associated with lower costs.

for dry matter and −0.51 for crude lipids. This suggests that the inclusion of IM in fish diets might not significantly enhance the ADC of dry matter and lipids compared to the control group, which utilized an insect-free diet. The observed low ADC values of dry matter and crude lipid, possibly due to antinutritional factors like chitin, protease inhibitors, and secondary metabolites as mentioned by Karlsen *et al.* (2015), highlight the complexities in achieving optimal efficiency. In this review, the average ADC of dry matter and crude lipid in the fish fed with the IM group was 74% and 89%, respectively, which were reported lower than those in the control group, which were 78% and 92%, respectively (data not shown). Although the fish fed with the IM group exhibited lower average ADC values for dry matter and crude lipid compared to the control group, the difference between the two groups was relatively

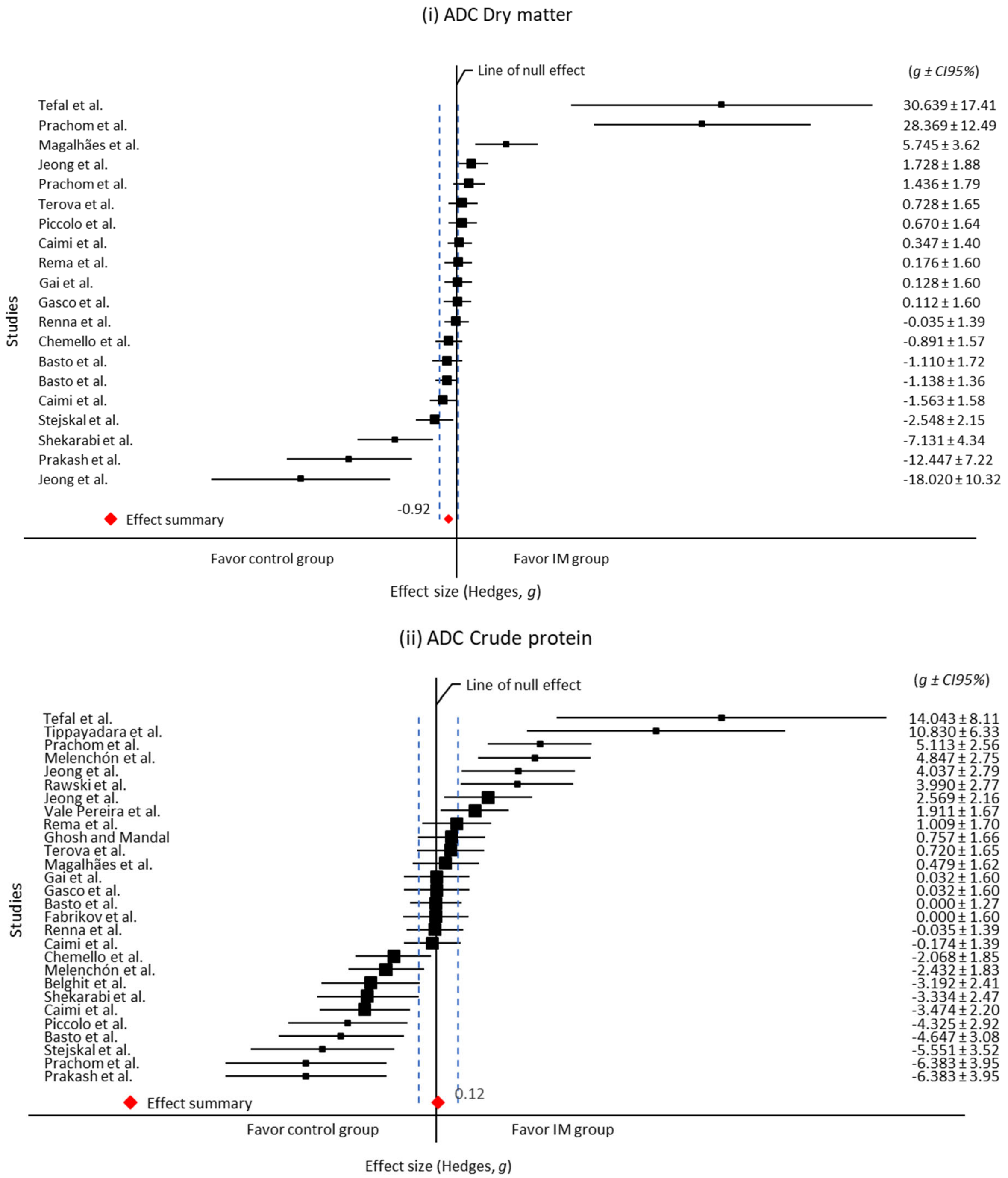

FIGURE 6 Apparent digestibility for (i) dry matter*, (ii) crude protein**, and (iii) crude lipid*** forest plot of effect sizes of fish fed with insect meals as a replacement for fishmeal. The summary of effect size, calculated according to a random effects model, is indicated by the red square. The size of the squares illustrates the weight of each study relative to the mean effect size with smaller squares representing less weight. CI = Confidence interval. *Average ADC dry matter in fish-fed IM and fish-fed IM-free diet are 74% and 78%, respectively. **Average ADC crude lipid in fish-fed IM and fish-fed IM-free diet are 89% and 92%, respectively. ***Average ADC crude protein in fish-fed IM and fish-fed IM-free diet are 89% each.

minor. This marginal difference explains the minimal impact observed in the effect summary.

Comparatively, studies examining various plant proteins, such as rice bran, maize bran, sago, banana peel, cocoa husk, and copra waste, on tilapia have reported a wider range of ADC for dry matter, typically falling between 50-70% (Yossa *et al.*, 2021a, b). Similarly, research on terrestrial animal proteins like blood meal and meat meal in rohu, *Labeo rohita* fingerlings, has shown lower ADC values of 42-57% (Hussain *et al.*, 2011). These findings emphasize the diverse ADC values across different protein sources, highlight-

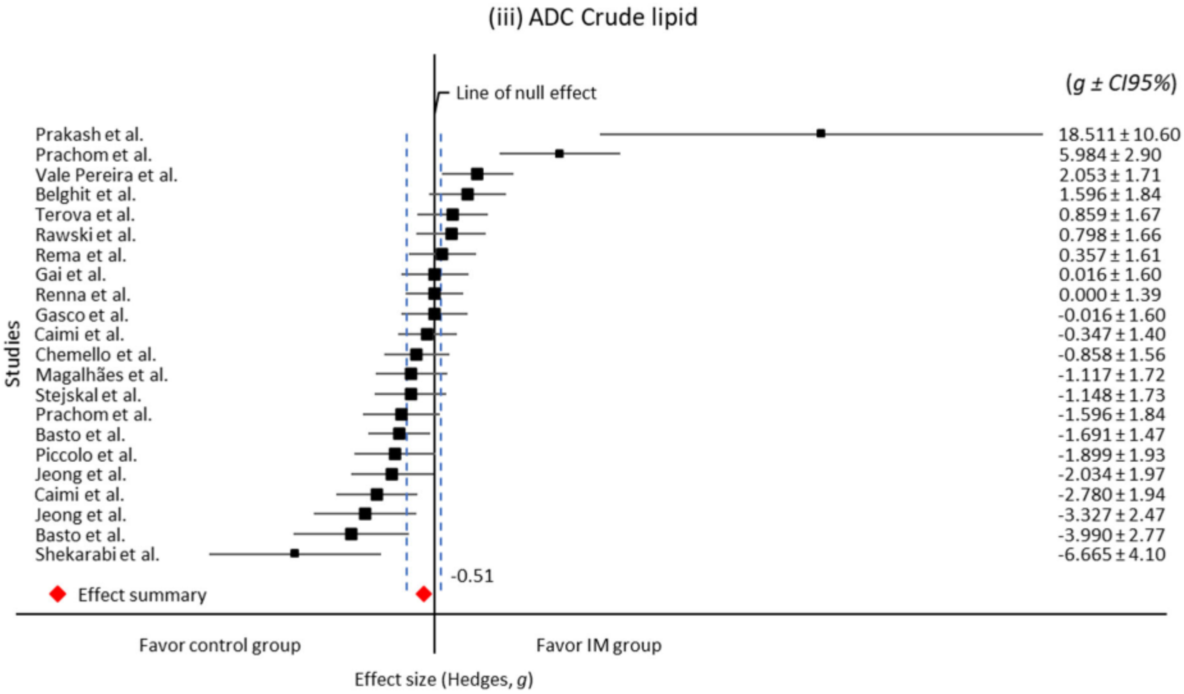

FIGURE 6 (Continued.)

ing the challenges in identifying optimal alternatives to FM for nutrient utilization. Despite the marginal differences from FM, IM exhibits a comparative advantage in supporting better nutrient utilization. The low ADC of crude lipids in fish fed with IM is probably due to the inefficiency in digesting and utilizing lipids from these substitutes, especially when the IM is not defatted and entirely replaces FM. Factors like high lipid and chitin levels in IM might pose challenges to efficient digestion, leading to lower ADC values. According to Sklan *et al.* (2004), fish demonstrated lower absorption rates for saturated fatty acids compared to polyunsaturated fatty acids. Johnsen *et al.* (2008) added that Atlantic salmon more efficiently absorbed polyunsaturated fatty acids than monounsaturated and saturated fatty acids, with decreasing absorption efficiency for longer-chain monounsaturated and saturated fatty acids. Gasco *et al.* (2022) demonstrated that defatted yellow mealworm and BSF, partially substituting FM, resulted in higher ADC of crude lipids, averaging 90%. This contrast underscores the influence of defatting and partial substitution on enhancing lipid digestibility in fish diets containing insect-based ingredients. Furthermore, Eggink *et al.* (2022) revealed species-specific differences in chitin digestion, with Nile tilapia and rainbow trout digesting chitin at rates of 59% and 50%, respectively. This suggests a varying ability among fish species to digest chitin, potentially contributing to the observed lower ADC of crude lipids when fish are fed with IM.

On the other hand, a positive effect summary was noted in the ADC of crude protein (0.12), was evident, indicating a favorable trend toward the IM group. This suggests a potential advantage in the utilization of protein by fish fed with IM-containing diets. The observed variability in the ADC of crude protein among studies further emphasizes the complexity of protein digestion and absorption in fish diets containing insect-based ingredients. The contrasting trend in crude protein digestibility, favoring the IM group, underscores the potential benefits of incorporating IM into fish feeds, particularly in enhancing the utilization of dietary protein. The high reported ADC values of crude protein in fish fed with IM, despite the ingredients not being dechitinized, suggest that the low digestibility of crude lipid in fish fed with IM might not solely result from the high chitin content. Instead, it may be attributed to the high lipid level in the IM, highlighting the need for a partially defatted process or partial substitution with FM, rather than total substitution. However, it's noteworthy that substantial heterogeneity was observed in the meta-analysis of ADC crude protein, highlighting the need for a nuanced approach to managing IM processing, which may be influenced by both the species of fish and the type of IM utilized. As the utilization of IM in aquafeeds continues to evolve, determining the digestibility and optimal inclusion levels for these alternative protein sources remains critical. The inclusion of IM in aquafeed formulations holds promise in augment-

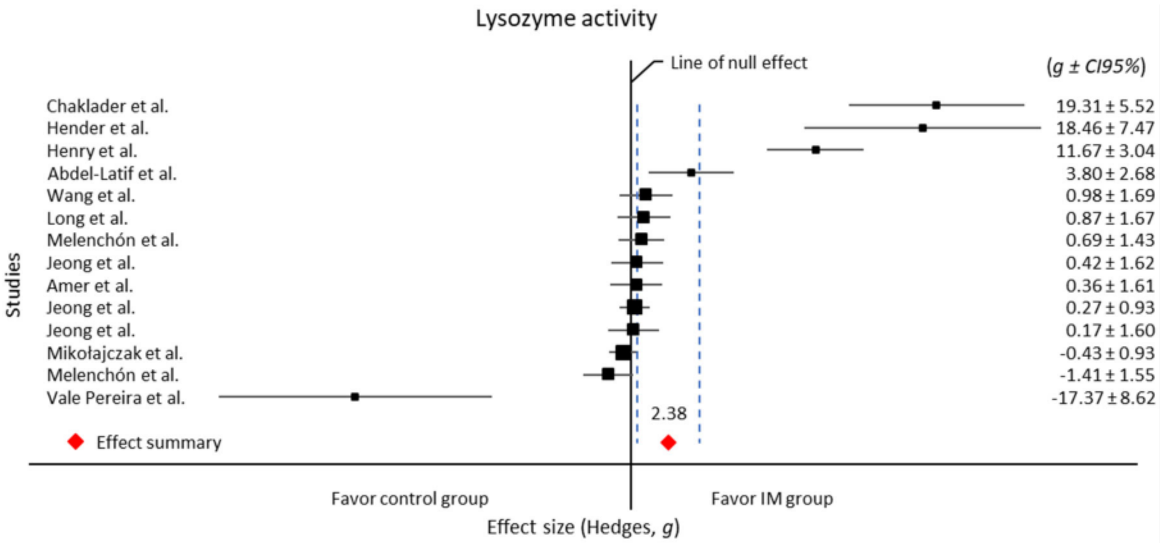

FIGURE 7 Non-specific immune parameter (lysozyme activity) forest plot of effect sizes of fish fed with aquafeed containing insect meal as a replacement of fishmeal. The mean effect size, calculated according to a random effects model, is indicated by the red square. The size of the blue squares illustrates the weight of each study relative to the mean effect size with smaller squares representing less weight. CI = Confidence interval.

ing fish protein digestion, yet the varying results underscore the necessity for further research to optimize their incorporation and understand their impact on overall nutrient utilization.

Fish blood parameters

The meta-analyses examining fish non-specific immune (lysozyme activity), blood metabolites (glucose, total protein, triglycerides, and cholesterol), and hematological parameters (hematocrit and monocytes) are summarized in Table 2, while their respective forest plots are depicted in Figures 7, 8, and 9.

In lysozyme activity, a positive effect summary was observed with a value of 2.38, indicating the parameter favoring the IM group over the control group (Figure 7). Lysozyme is considered an essential component of the innate immune system in fish and many other organisms. Its importance lies in its ability to defend against bacterial infections by acting as a prebiotic thus modulating the gut microbial communities of fish. The low levels of lysozyme activity in fish might indicate fish stress or disease. The present findings suggest that IM can be an excellent candidate for partial FM replacement, possibly resulting from the presence of chitin that helps enhance the immune response in fish (Purkayastha and Sarkar, 2020). Reportedly, the inclusion of yellow mealworm at 67% FM replacement showed a better immune response in the rainbow trout as demonstrated by Henry *et al.* (2018). In other studies, Rimoldi *et al.* (2023) compared chitin derived from 20.4% shrimp waste meal and FM with added 1.6% BSF prepupae exuviae and successfully demonstrated that chitin present in BSF meal was better at modulating gut microbiota communities of rainbow trout. Soetemans *et al.* (2020) outlined that the distinction between chitin in crustaceans and insects primarily lies in the composition of nanofibers; shrimp chitin comprises nanofibers with varying thickness but lacking pores, whereas BSF chitin contains discernible pores. Rimoldi *et al.* (2023) added that variations in chemical composition, structural attributes (i.e. surface and porosity), and solubility of chitin can significantly influence its bio-accessibility. This evidence strongly suggests that incorporating chitin-rich, particularly from insects into fish feeds may bolster disease resistance, improve immune system functionality, and potentially reduce the reliance on FM, thereby offering a more sustainable and immunologically beneficial alternative in aquaculture practices.

As for blood metabolites, understanding their profile is pivotal, offering a quick assessment of the fish's health and metabolic state in response to dietary alterations or stress (Ahmed *et al.*, 2023). Key indicators such as blood glucose levels, reflecting carbohydrate metabolism, triglycerides indicating lipid utilization, total protein denoting overall protein synthesis and health, and cholesterol as a vital lipid component, provide insightful metrics. Analyzing these parameters becomes essential in evaluating the suitability of IM in fish diets. Notably, our review demonstrates varying effects, with glucose and triglycerides showing a positive impact favoring the IM group (Figure 8). As such,

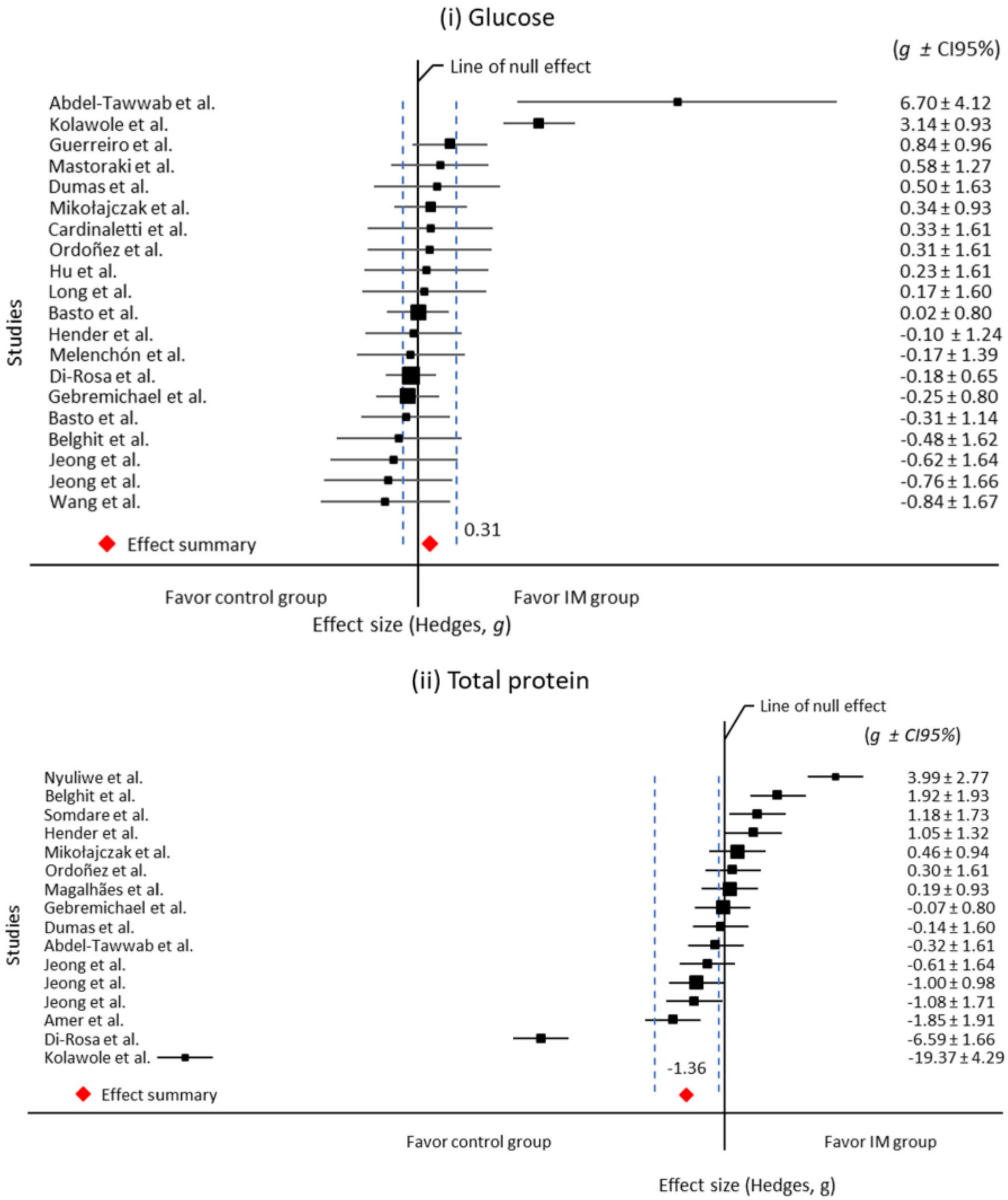

FIGURE 8 Blood metabolite parameters forest plot of effect sizes for (i) glucose, (ii) total protein, (iii) triglycerides, and (iv) cholesterol of fish fed with aquafeed containing insect meal. The summary of effect size, calculated according to a fixed effect model for glucose and random effects model for total protein, triglycerides, and cholesterol which is indicated by the red square. The size of the squares illustrates the weight of each study relatively to the mean effect size with smaller squares represent less weight. CI = Confidence interval.

glucose and triglycerides exhibited a positive effect summary with values of 0.31 and 0.84, respectively, signifying a magnitude that favors the IM group. These changes indicate improved carbohydrate and lipid metabolism, which is directly related to the high ADC of lipid as discussed previously. This improvement can lead to better energy utilization and growth performance in fish. The enhanced carbohydrate metabolism, evidenced by improved blood glucose levels, indicates more efficient use of carbohydrates for energy. Meanwhile, the improved lipid metabolism, resulting from the high ADC of lipid, supports better energy storage and utilization. These metabolic enhancements can be observed in the high growth performance reported in sturgeon (Rawski *et al.*, 2020), snakehead (Prachom *et al.*, 2023), and rainbow trout (Prakash *et al.*, 2023; Vale Pereira *et*

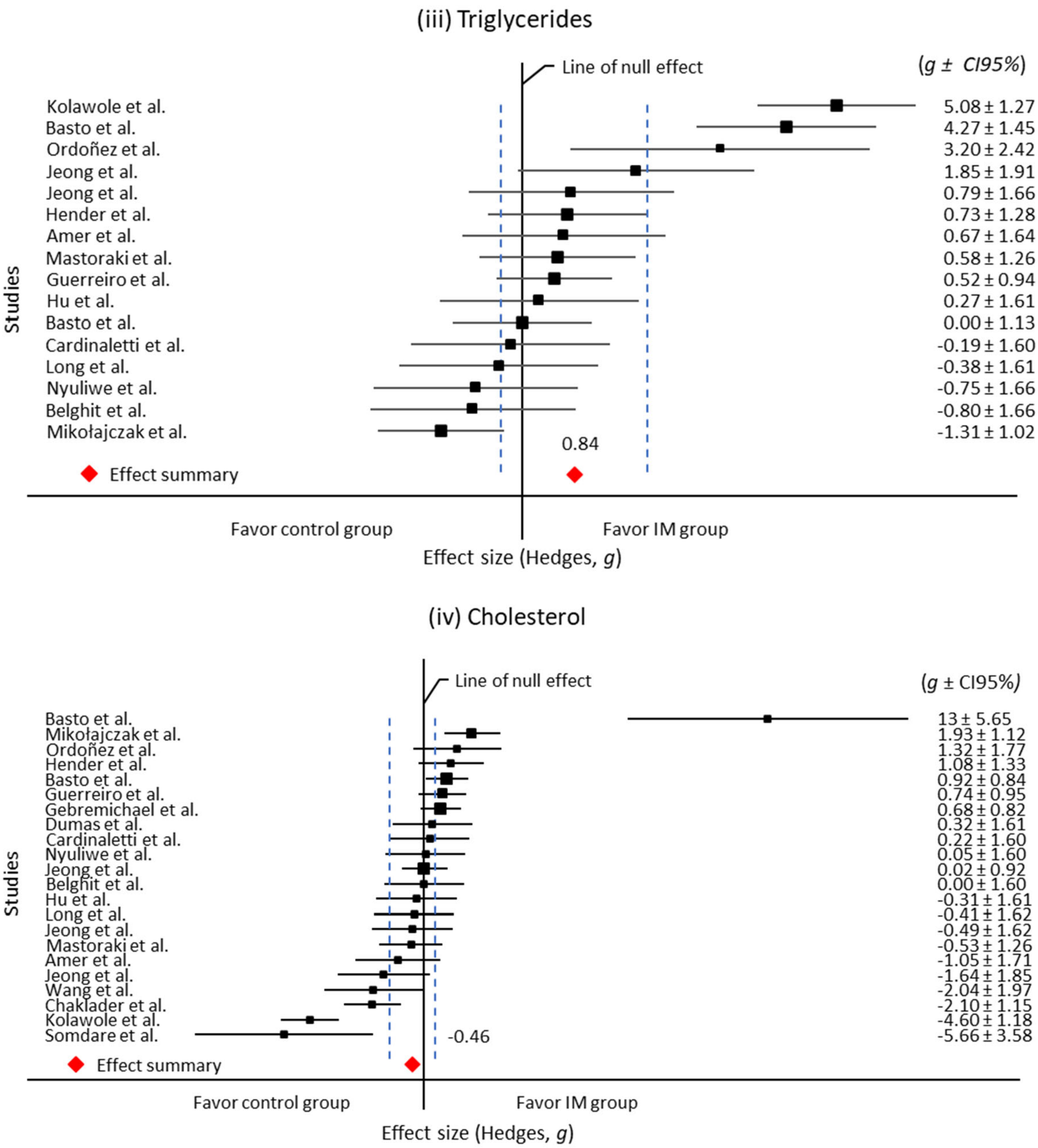

FIGURE 8 (Continued.)

al., 2023). While proteins and amino acids primarily impact glucose metabolism (Shwetha *et al.*, 2012), the suggestion that specific proteins or amino acids from the IM diet may have a more favorable effect on regulating blood glucose levels compared to those derived from FM, hints a potential correlation between dietary protein sources and blood glucose control in fish. This aligns with Ahmed *et al.*'s (2023) study, indicating that *C. carpio* exhibited higher blood glucose levels when fed an *Azolla* meal than the FM. It's an example of how specific alternative feeds, like *Azolla* meal, can affect fish metabolites. Meanwhile, the higher blood triglycerides in fish fed with IM compared to the FM may be attributed to certain components or nutrients such as fatty acid composition which might trigger metabolic pathways that result in elevated triglyceride levels in the blood. Additionally, the high blood lipid content in fish fed with IM is closely related to the lipid content of IM itself, highlighting how the lipid composition of IM influences blood lipid profiles in fish. Since triglycerides are essential for energy storage, moderately higher levels can be advantageous for fish growth and energy reserves. This underscores the importance of partial FM replacement with IM, rather than total replacement, to optimize growth and metabolic health in fish. However, as triglycerides are essential for energy storage, exces-

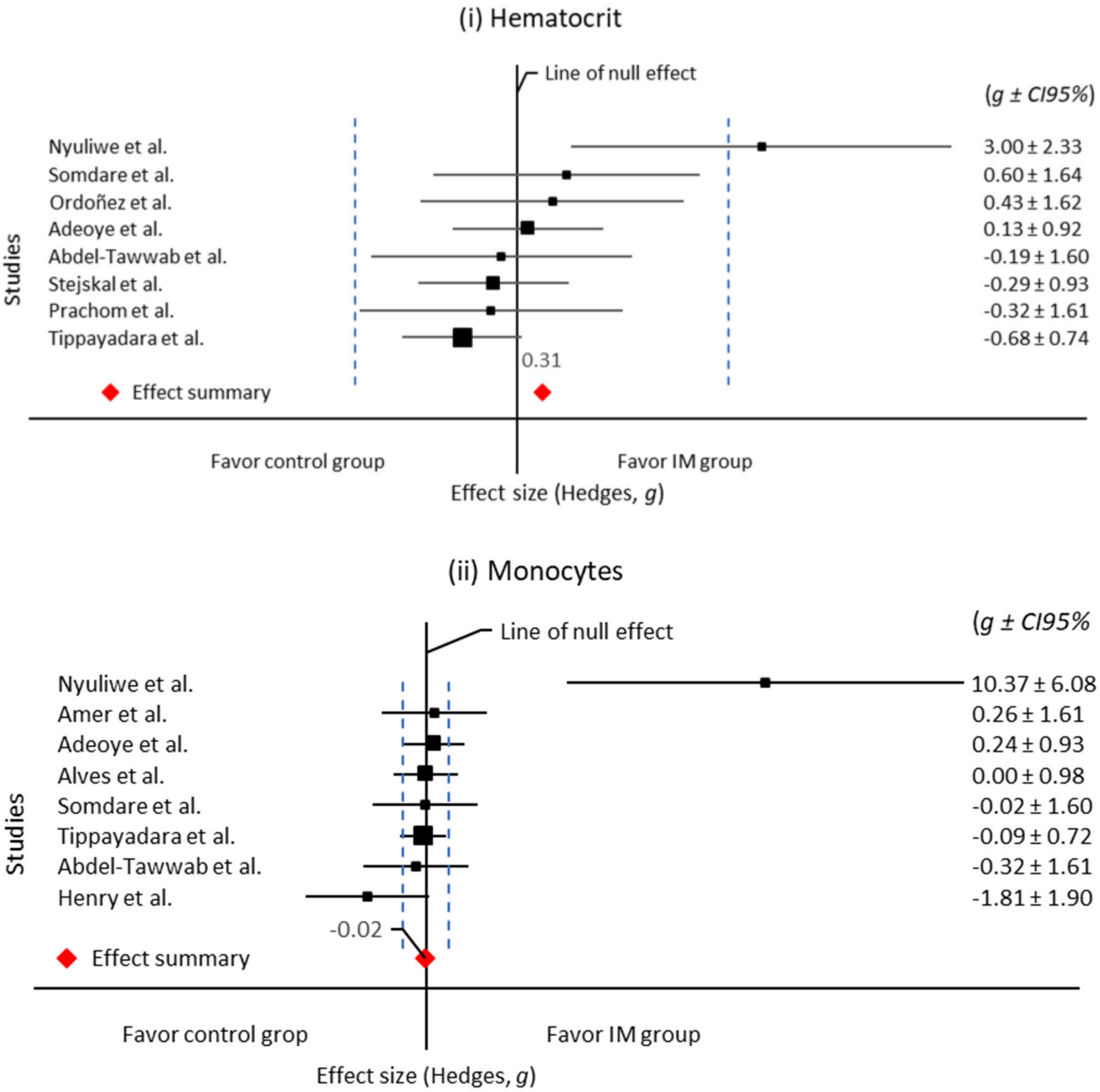

FIGURE 9 Hematological parameters forest plot of effect sizes for (i) hematocrit and (ii) monocytes of fish fed with aquafeed containing insect meal. The summary of effect size, calculated according to a random effects model, indicated by the red square. The size of the squares illustrates the weight of each study relative to the mean effect size with smaller squares representing less weight. CI = Confidence interval.

sively high levels might hint at imbalances or health concerns.

Conversely, both total protein and cholesterol showed negative effect summaries (−1.36 and −0.46, respectively), potentially linked to deficiencies in certain amino acids and cholesterol, resulting in decreased bloodstream levels. Fish might encounter challenges in digesting nutrients from IM, impacting overall nutrient absorption and utilization, as observed with leafworm meal (Amer *et al.*, 2021) and mealworm (Jeong *et al.*, 2020). However, the inclusion of BSF in fish diets did not affect blood total protein and total cholesterol levels (Zhou *et al.*, 2018; Guerreiro *et al.*, 2020; Hender *et al.*, 2021). These conflicting outcomes in blood metabolite levels, observed across various studies on different fish species, might be attributed to varying fish tolerance levels towards different insect species used in diets. While deficiencies in certain amino acids and cholesterol in IM could decrease total protein and cholesterol in the bloodstream, not all insect sources, like BSF mentioned in several studies, seem to yield the same impact on these blood metabolites. This discrepancy suggests that fish species might react differently to various insect-based diets, affecting their ability to digest and utilize nutrients from these alternative feed sources.

On the other hand, hematological parameters linked to the non-specific immune function serve as reliable indicators of overall fish health and their response to dietary changes or stressors (Jeong *et al.*, 2020). A positive summary effect was observed in hematocrit (0.31), while a negative summary effect was noted in monocytes (−0.02), albeit with only a slight difference (Figure 9). These findings suggest that the fish were generally in good health and could tolerate IM in their diets, despite a slightly lesser impact compared to FM. Studies by Abdel-Tawwab *et al.* (2020), Alves *et al.* (2020), and Tippayadara *et al.* (2021) reported that the difference in monocyte count between fish fed with IM and FM is not significant, explaining this marginal difference. It might be insightful to explore whether the slight variations observed in monocytes, despite the overall good health of the fish, could be linked to the chitin content present in the IM diets.

Considering all the findings on fish blood parameters, it is a noteworthy aspect that demands our attention. The significant impact of replacing FM with IM on fish blood parameters further strengthens the proposition that IM can serve as a viable alternative. We recommend a cautious approach to incorporating IM into fish diets to safeguard fish health. Given the notable impact of IM on fish blood parameters, further investigations are necessary. Revisiting this subject with comprehensive research findings will facilitate the identification of diverse factors influencing fish responses to IM in their diets.

Economic performance

As IM is considered a novel ingredient, early opinions on feed cost analysis seem unfavorable towards the use of IM in terms of reducing feed cost management. This economic disparity is frequently attributed to the relatively high cost of IM compared to FM. As elucidated by Mulazzani *et al.* (2021), the current cost of IM, ranging from €3.5 to €7/kg in Europe, reflects the ongoing lack of competitive production scale. Arru *et al.* (2019) posited that this cost differential plays a pivotal role in the observed trends. A transitional period is necessary to establish a stabilized and economically accessible price point.

However, our findings noted that the underlying effect summaries show a positive favor toward the IM group, indicating that lower costs were incurred during the experiment compared to the control group. The meta-analysis revealed effect summaries of −0.08 for feed cost and 0.00 for the economic profit index, indicating better economic performance in the IM diet (Figure 10, Table 2) in terms of both feed cost and economic profit index. The growing interest in IM production has driven the global expansion in the IM industry, fostering a scenario where IM prices align more closely with those of FM. A market analysis in China conducted by Zhang *et al.* in 2019 showed that processed by-product protein meals such as mushroom spent corn stover, highly denatured protein SBM, and distillers' grain were priced at US $100, US $300, and US $150 per ton, respectively. Meanwhile, the price of dried mealworm larvae during that time was around US $5,000 per ton (Zhang *et al.*, 2019), which was pricier than traditional protein sources, making it less accessible for widespread use in animal feed. Today, our online market survey in China indicated a stagnant price for dried mealworms, with a slight reduction to US $4,700 per ton using the Made-in-China platform. In contrast, cricket meal and dried BSF were, respectively, priced at US $3,900 and US $2,500 per ton on the Alibaba platform, reflecting significant shifts in the market for insect-based protein feeds in China. Although the price of dried mealworm larvae has remained relatively stable, indicating steady demand possibly due to established market use, its high cost remains a barrier to widespread adoption compared to other protein sources. On the other hand, the price of dried BSF has halved over the past five years. The observed trends in BSF prices suggest significant market shifts, attributed to increased production efficiency, scaling, and growing market acceptance. Additionally, BSF is widely produced in China, the largest distributor, possibly due to their efficient conversion of organic waste into high-protein biomass (Kim *et al.*, 2021; Purnamasari and Khasanah, 2022), which creates price competition and explains the cost difference compared to other IMs. Conversely, mealworms are generally more expensive because they require more controlled rearing environments compared to BSF, which can thrive on a wider range of feed sources such as kitchen waste, manure, fecal sludge, and distillers' byproducts (Seyedalmoosavi *et al.*, 2022).

At the same time, market prices in the US show similarity to those in China based on our online market survey. Our survey on the Alibaba platform found that most US suppliers sell IM originating from China, explaining the price similarity. This could be attributed to labor and regulatory compliance costs that make US-produced IM less competitive compared to other countries. However, our market analysis is focused exclusively on the Alibaba platform. There may be variations on other platforms; for example, US suppliers might produce their own IM. Surprisingly, our online market analysis of IMs from European countries such as the Netherlands on the Alibaba platform shows that dried BSF is priced at around USD 800 per ton, while mealworms are priced at US $100 per ton, significantly cheaper than in the Chinese market. Our assumption is that these price dif-

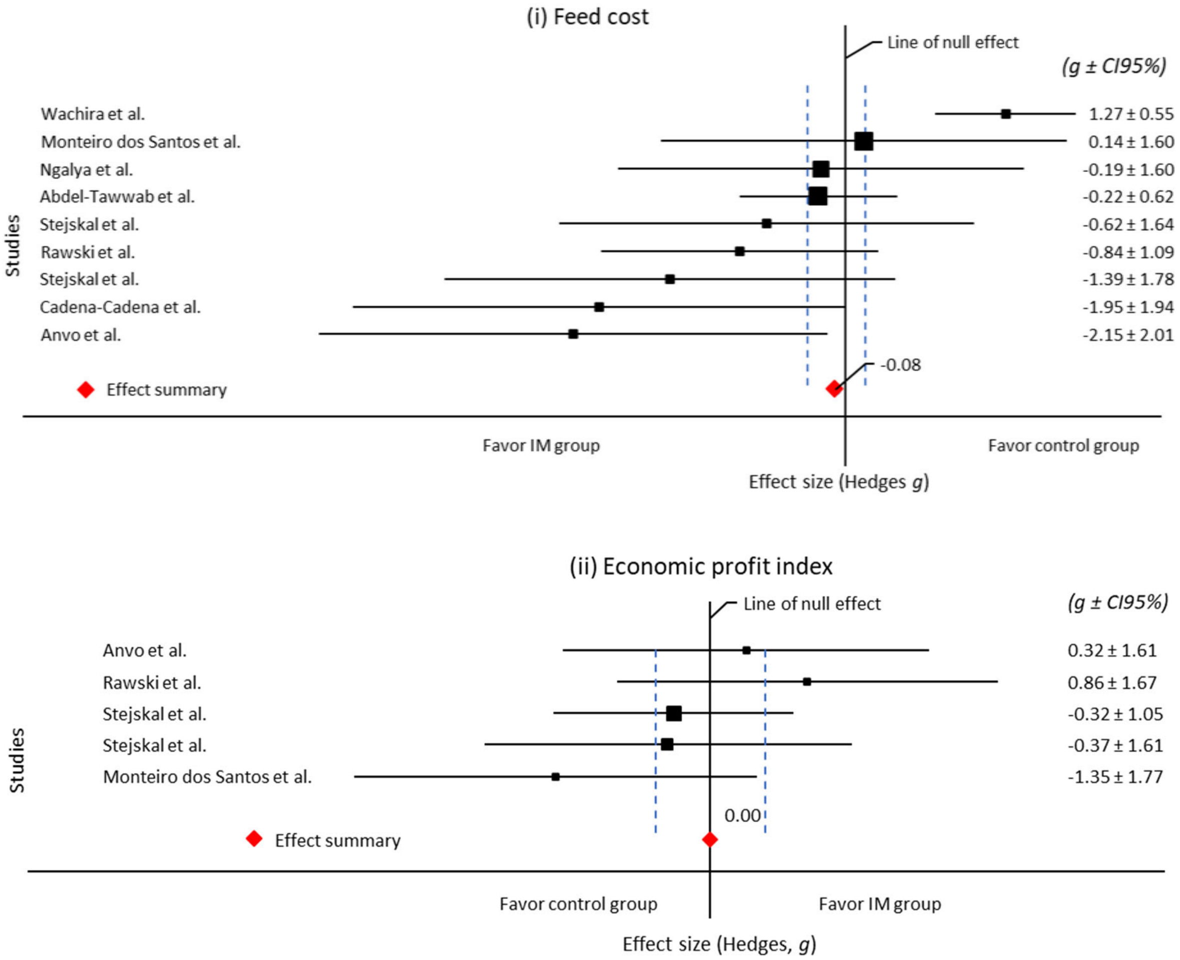

FIGURE 10 Economic performance forest plot of effect sizes for (i) feed cost and (ii) economic profit index of fish fed with aquafeed containing insect meal. The summary of effect size was calculated according to a fixed effects model, indicated by the red square. The size of the squares illustrates the weight of each study relative to the mean effect size with smaller squares representing less weight. CI = Confidence interval.

ferences may be influenced by varying production costs, regulatory environments, and market demand dynamics across different regions. In Africa, including countries like Kenya and South Africa, the price of BSF meal ranges from US $2,000 per ton. Overall, these price disparities reflect the complex interplay of local factors affecting the production, distribution, and demand for insect-based protein feeds globally. Zhang *et al.* (2019) added that despite cost differences among protein by-product feedstuffs, insect rearing demonstrates stronger sustainability and efficiency in transforming plant biomass into animal biomass compared to conventional feedstocks. These price trends underscore the increasing economic viability of insects, particularly BSF, as a protein source, aligning with global trends towards sustainable agricultural practices. Overall, these developments in the insect-based protein market, particularly in China, are positive for agricultural sustainability. IM production not only offers efficient biomass conversion and environmental benefits through waste utilization but also contributes to local economic development by creating jobs in farming, processing, and distribution sectors. Continued innovations and increased production capacities are expected to further enhance affordability and market acceptance of these alternative protein sources.

Overall, these developments in the insect-based protein market are positive for agricultural sustainability. Continued innovations and increased production capacities are expected to further enhance affordability and market acceptance of these alternative protein sources. Moreover, through consultations with experts, we have found that IM production not only offers efficient biomass conversion and environmental benefits through waste utilization but also contributes significantly to local economic development by creating jobs in farming, processing, and distribution sectors. This dual benefit makes IM a promising source of income for households while aiding environmental sustainability. Still, we recommend conducting additional research in this field to further validate and solidify these findings, considering the lack of degree of freedom in the current study as the scarcity of data hampers a comprehensive understanding of these dimensions (Turner *et al.*, 2013).

4 Future perspectives on the insect feed industry

Despite initial concerns about human acceptance, analysis of the impact of IM on fish welfare and aquaculture cost management has demonstrated its successful use as a substitute for FM in aquafeed. Future studies investigating IM offer a clear opportunity to deepen our understanding of its positive effects on fish health and performance. Shifting focus from traditional measures to markers directly linked with fish health and immune response can provide more precise insights. Moreover, exploring various components of IM, such as lipids, functional elements such as chitin, through simplified breakdown methods, can significantly enhance our comprehension of their nutritional value. Analyzing how each part influences fish health when reintroduced step by step offers valuable insights into the benefits of IM. As IM emerges as a potential solution for global food security and sustainability, our findings shed light on the crucial role legislation can play in facilitating its acceptance and integration. However, differing regulations across countries pose safety and consumer acceptability concerns, hindering insect-based aquafeed growth. Future research should prioritize comprehensive life cycle assessments to understand IM's impact on aquaculture development and economics.

5 Conclusion

The advancement of insect feed technology, particularly IM, holds substantial promise for enhancing aquafeed quality and improving fish performance. Current research consistently demonstrates positive effects on fish growth and financial outcomes, yet further exploration is needed to fully understand the welfare implications and economic viability of integrating IM into aquafeed systems. Our review underscores the potential of IM in enhancing fish digestibility, with numerous studies reporting improved nutrient absorption and growth metrics when IM partially or fully replaces FM. We advocate for the partial replacement of FM with IM, recognizing FM's superiority in EFA and EAA. Analysis of blood parameters, including glucose and triglycerides, indicates that IM can positively influence fish health and metabolic states. However, achieving balanced nutrient profiles remains a challenge to prevent potential deficiencies in total protein and cholesterol levels. Economically, IM offers a promising alternative to FM by potentially reducing feed costs and promoting sustainable aquaculture practices. Nonetheless, its economic performance requires further investigation, especially in large-scale operations, to validate its cost-effectiveness and market acceptance. As the aquaculture industry continues to evolve, IM stands poised to become a competitive and sustainable alternative to traditional FM, offering benefits to both aquaculture practices and environmental sustainability.

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Conflict of interest

The authors have no conflict of interest to declare.

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