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Review Article

Replacement of Fishmeal in the Diet of African Catfish (*Clarias gariepinus*): A Systematic Review and Meta-Analysis

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ABSTRACT

Fishmeal is widely accepted as a protein source in fish feed formulation, making it a highly demanded ingredient, and this has probably contributed to its increased cost. Cheaper protein sources of plant and animal origin have been tested as potential replacements for fishmeal to reduce feed costs in fish production and guarantee a suitable nutrient supply for adequate growth. Therefore, this review assessed the effect of replacing fishmeal in the diet of African catfish, *Clarias gariepinus* based on empirical findings. Using a systematic literature review protocol, an extensive search of five databases resulted in the final inclusion of 32 articles for appraisal

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and meta-analysis. Fishmeal replacements were at levels ranging from 7–100%, while fish survival rate and feed conversion ratio recorded non-significant effects of fishmeal replacement ($p > 0.05$). However, final weight, weight gain, specific growth rate, and protein efficiency ratio revealed a significant effect of fishmeal replacement ($p < 0.05$) in the diet of African catfish. Our overall analyses suggest that feed ingredients such as microalgae and insects/worms are potentially perfect replacements for fishmeal.

Keywords: African catfish, alternative protein, aquaculture, fish growth, food security, nutrient utilization

INTRODUCTION

Over the years, aquaculture has increasingly contributed to the overall production of food fish, making it an essential practice that can help reduce hunger and improve food security in line with the United Nations' Sustainable Development Goals. A significant proportion of the costs involved in farmed fish production is related to feeds and feeding because of the high cost of protein-rich ingredients like fishmeal (Ansari et al., 2021; Tilami et al., 2020; Wan et al., 2019). Like fish species, feed ingredients differ in their nutritional characteristics and possible inclusion and replacement levels (Adeyemi et al., 2020). Therefore, the protein content, amino acid profile, and digestibility of the feed ingredients will influence their inclusion for replacement, making it crucial to ensure that the ingredients used for feed formulation possess the required nutrients for adequate growth and utilization by the fish species.

Being a source of protein, which is highly-priced, fishmeal is regarded as an essential ingredient in the diet of carnivorous and omnivorous aquatic organisms, mainly fishes (Alhazzaa et al., 2019; Olsen & Hasan, 2012). Consequently, efforts have been made to replace fishmeal partially or wholly with alternative protein sources in the diet of fish species. These efforts have sought to achieve similar or better output like fishmeal at a reduced cost (Adewolu et al., 2010; Ojewole et al., 2022; Raji et al., 2018; Taufek et al., 2016a).

Scientists must develop new strategies to provide the required amounts of high-quality protein to meet the growing demand (Boland et al., 2013). More so, a potentially viable feed component to replace fishmeal in aquafeeds must be at a reasonable cost, readily available, and simple to handle, transport, store, and use in feed production (Musyoka et al., 2019). Furthermore, high protein content, good amino acid profile, low-fat content, and excellent nutrient digestibility are some of the required characteristics (Luthada-Raswiswi et al., 2021).

Protein sources of plant and animal origin have been used in different fish species to replace fishmeal. In some cases, the growth, nutrient utilization, and other information such as enzyme activity and hematological parameters have been compared for fish (Huda et al., 2020; Kim et al., 2021; Lawal et al., 2017; Pongpet et al., 2016; Tippayadara et al., 2021; Wang et al., 2018; Zheng et al., 2012) and shellfish (Moniruzzaman et al., 2020). Aside from fishmeal, several alternative feed ingredients, such as those of animal protein origin, insects, land animal by-products, fisheries by-products, worms, and plant-based protein sources, including algae such as *Chlorella* and spirulina, have been evaluated as feed ingredients in both fresh and marine water fish production (Ansari et al., 2021; Raji et al., 2018, 2019; Saleh, 2020).

Fishmeal has been totally or partially replaced in species' diets, such as tilapia *Oreochromis niloticus* (Abarra et al., 2017; Arunlertaree & Moolthongnoi, 2008; Djissou et al., 2019; Yousif et al., 2019), Atlantic salmon *Salmo salar* (Belghit et al., 2019), rose snapper *Lutjanus guttatus* (Hernández et al., 2014), snakehead *Channa argus* (Yu et al., 2015), and Russian sturgeon *Acipenser gueldenstaedtii* (Gong et al., 2016), among other species. Novriadi et al. (2017) performed a meta-analysis of fishmeal replacement with soybean meal. However, the African catfish *Clarias gariepinus* was not captured in the analysis. Luthada-Raswiswi et al. (2021) systematically reviewed and meta-analyzed the substitution of fishmeal by animal protein sources in aquaculture diets with valuable information about an array of fish species in whose diets fishmeal was replaced. Unfortunately, the study was not structured to assess individual fish species in-depth.

African catfish is an economically important fish species extensively cultured in various parts of the world. Especially in the tropics, due to its ability to accept a wide variety of feed, breed in captivity, grow fast, tolerate high stocking density, and resist common diseases (Abdel-Warith et al., 2019; Musa et al., 2021; Tahir et al., 2021). Fishes belonging to the genus *Clarias* are among the significant fish species produced worldwide, where approximately 2.3% of the world's catfish farming has contributed to total fish production (Food and Agriculture Organization of the United Nations [FAO], 2020). Efforts geared towards the further increase in its production through a reduction in the cost of feeding, its sustainability, and efficiency by using cheap but highly nutritious and sustainable ingredients are, therefore, outstanding contributions to food security around the globe. However, despite previous efforts, information regarding the performance of African catfish fed with diets where fishmeal was replaced partially or entirely remains scattered in the literature, making it challenging to identify the alternative feed ingredients with the best potential for growth and nutrient utilization of this species. Therefore, this study aims to systematically review existing studies regarding the replacement of fishmeal in the diet of African catfish. Besides, a meta-analysis to compare the recommended replacement levels of diets against the control was also conducted.

More specific information on these alternative protein sources may reduce feeding costs, increase growth and nutrient utilization parameters, and, therefore, add to the profits of fish farmers. Besides, there is a potential contribution of such information to increased production of African catfish and fish food from the aquaculture sector due to efficient growth and nutrient utilization by the fish species. The successful replacement of fish meals in the diet of African catfish with cheaper yet nutritive alternatives can boost its production. This inclusion will improve aquaculture's contribution to food and nutrition security across the globe.

MATERIALS AND METHODS

Database Search and Screening

A search of databases, such as Scopus (https://www.scopus.com/), ScienceDirect (https://www.sciencedirect.com/), ProQuest (https://www.proquest.com/), and Wiley Online Library (https://onlinelibrary.wiley.com/), was conducted in addition to a search of the Google Scholar (https://scholar.google.com/) database. The following terms or phrases were used: "fishmeal replacement in "*Clarias gariepinus*", "fishmeal alternative in *Clarias gariepinus*", and "fishmeal substitution in *Clarias gariepinus*". The search was not limited to any time duration. From the databases, results produced for each search were exported as comma-separated values (CSV), research information systems (RIS), or text (txt) files to Rayyan QCRI (Qatar Computing Research Institute) software (Disner et al., 2021; Ouzzani et al., 2016). Rayyan is a free online tool for academics working on systematic review methodology and meta-analysis projects. Rayyan is one of several software products developed by QCRI, a creative and imaginative body of the Qatar Foundation for Education, Science, and Community Development, akin to the United States Department of Education in many aspects. Users may contribute citations and full-text articles as part of a single review, create several review projects, and even collaborate on publicly available projects using Rayyan (Johnson & Philips, 2018).

Duplicates were removed, after which articles were included or excluded based on title and abstract screening using predetermined criteria. Next, the first 500 publications from the Google Scholar search were screened for inclusion (Algera et al., 2020). Finally, the included articles were all downloaded for full-text screening. Studies included in the review were those published between the years 2010 and 2021 and reported at least three of the following: survival rate, growth parameters: final weight (FW), mean weight gain (MWG), and specific growth rate (SGR); nutrient utilization parameters: feed conversion ratio (FCR) and protein efficiency ratio (PER). Studies in which there were either no replicates, did not have a design directly related to the replacement of fishmeal, or did not provide clear information regarding the percentage replacement of fishmeal were excluded. For continuous data analysis, those with zero standard deviation (SD) values are not estimable and were excluded from the study. At the same time, data with the same percentage survival for the control and experimental groups are also non-estimable and, therefore, excluded.

Statistical Analysis

Microsoft Office Excel 2016 (Microsoft Inc., USA) was used to compute descriptive information about the included studies, while meta-analyses were conducted using Review Manager (RevMan) version 5.3 software for narrative synthesis. The primary outcome of this study was the performance of fish fed a fish meal-replaced diet in terms of growth and nutrient utilization. The odds ratio (OR) with 95% confidence intervals (CIs) for dichotomous data and standardized mean difference (SMD) with 95% CIs for continuous data were used to determine the relationship between fishmeal replacement and survival level. The forest plot was used to show pooled estimates. When the outcomes were not accessible, missing data were entirely random. In some cases, one study reported replacing fishmeal with more than one alternative ingredient, and these were treated individually, although with the same information for the control.

RESULTS

Database Search and Screening

A search of five databases yielded 2,562 individual records, with 2,021 articles remaining after duplicates were removed (Figure 1). After title and abstract screening, 112 articles were left for full-text screening. Seventy-four (74) publications were deleted from full-text screening for various reasons, including non-reportage of pertinent data, while six were excluded during data extraction. There were no more publications for data extraction after the full-text screening of grey literature sources from online searches.

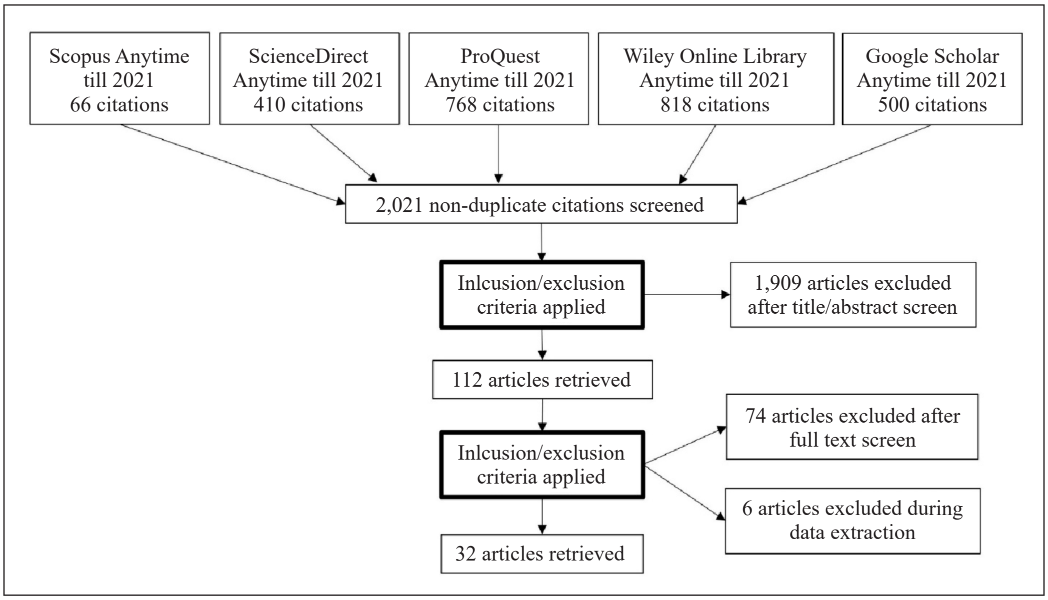

Figure 1. Flowchart of the database searched, screened, and included studies prepared using the PRISMA Flow Diagram Generator by Toronto Health Economics and Technology Assessment Collaboration (http://prisma.thetacollaborative.ca/)

Feed Ingredients and Recommended Replacement Levels

The included articles identified three main categories (animal products, insects/worms, and plant products) of protein sources used to replace fish meals in the diet of African catfish. The "animal products" being the first category include blood meal, poultry by-products, fish viscera, and shrimp heads. Various insects, including palm grub, palm weevil, black soldier fly, grasshopper, cricket meal, and worms, such as mopane and earthworm, were grouped under the second category, "insets/worms". Finally, the third category, or "plant products", consisted of spirulina, *Chlorella*, velvet bean, corn gluten, moringa leaf, marine seaweed, Bambara nut, and sweet lupin meal. The recommended replacement levels were 10–100% for insects/worms (with the highest recommended levels recorded for earthworm and maggot meal mix and cricket meal), while plant products had recommended replacement levels ranging from 10–75% (with the highest recommended levels recorded for spirulina and *Chlorella*). Generally, the feeding trial experiments ranged from 35 to 86 days, mostly feeding two times a day at 2.5–10% of fish body weight (Table 1).

Table 1
Summary of studies that assessed fishmeal replacement in the diet of African catfish using animal products, insects/worms, and algae/plants

	RRL (%)	D (days)	FF (times/ day)	FP (%BW)	NF	NR	Study
Animal products							
Cow blood meal	7.0	51	2	5	15	3	Ogunji et al. (2020)
Donkey blood meal	7.0	51	3	5	15	3	Ogunji et al. (2020)
Fish visceral meal	30.0	56	2	5	15	3	Jimoh et al. (2021)
Poultry offal meal	50.0	84	NS	5	10	3	Mamoon et al. (2018)
Blood and rumen blend	25.0	70	2	4	10	2	Lawal et al. (2017)
Blood meal and bovine rumen blend	50.0	86	2	5	12	2	Adewole et al. (2014)
Poultry offal meal	30.0	70	3	5	10	3	Falaye et al. (2011)
Snail offal meal	50.0	70	2	5	20	3	Okanlawon and Oladipupo (2010)
A mix of chicken feather and maggot	50.0	56	2	3	10	3	Adewolu et al. (2010)
Shrimp head meal	20.0	84	2	4	20	3	Nwanna et al. (2004)
Insect/worms							
Palm weevil meal	100.0	70	2	5	20	3	Agbanimu et al. (2020)
Black soldier fly meal	50.0	35	3	6	25	3	Huda et al. (2020)
Black soldier fly meal	50.0	42	2	AL	30	3	Adeoye et al. (2020)
Cricket meal	100.0	56	2	5-10	15	3	Taufek et al. (2018)

Table 1 *(continue)*

	RRL (%)	D (days)	FF (times/ day)	FP (%BW)	NF	NR	Study
Earthworm and maggot meal mix	100.0	42	3	5	50	3	Arnauld et al. (2016)
Earthworm meal	70.0	84	2	5	20	3	Monebi and Ugwumba (2016)
Cricket meal	75.0	49	2	AL	10	3	Taufek et al. (2016)
Variegated grasshopper meal	25.0	56	2	5	10	3	Alegbeleye et al. (2012)
Mopame worm meal	10.0	51	2	AL	100	3	Rapatsa and Moyo (2019)
Algae/plants							
Spirulina	68.5	56	2	4	10	3	Raji et al. (2019)
Chlorella	69.4	56	3	4	10	3	Raji et al. (2019)
Sweet lupin	50.0	63	3	5	10	3	Yalew et al. (2019)
Spirulina	75.0	84	2	2	15	3	Raji et al. (2018)
Chlorella	75.0	84	2	2	15	3	Raji et al. (2018)
Fenugreek seed meal	18.0	60	2	AL	30	3	Sheikhlar et al. (2018)
Corn gluten meal	50.0	70	2	NS	10	3	Adebayo and Obe (2017)
Moringa	15.0	56	2	5	10	2	Idowu et al. (2017)
Moringa leaf meal	10.0	56	2	5	10	3	Ezekiel et al. (2016)
Marine seaweed	10.0	70	2	3	15	3	Al-Asgah et al. (2016)
Bambara nut meal	75.0	56	NS	3	20	2	Orire et al. (2015)
Velvet bean	10.0	70	2	5	50	2	Aderolu et al. (2009)
Processed flamboyant meal	40.0	70	2	5	20	2	Adesina and Agbatan (2021)

Note. RRL (%) = Recommended replacement level in percentage; D = Duration of days; FF = Feeding frequency in times/day; FP = Feeding pattern in % body weight; NF = Number of fish per tank; NR = Number of replicates; AL = *Ad libitum*; NS = Not state

Survival, Growth, and Nutrient Utilization Parameters

Of the 32 included studies, 14, 28, 26, 31, 26, and 24 cases reported the survival rate, final weight, mean weight gain, specific growth rate, feed conversion ratio, and protein efficiency ratio, respectively, for both control and experimental groups of African catfish. The percentage survival of African catfish from the studies assessed recorded a mean of 89.40±5.30%. This value ranges from 77.78% to 100.0% for the control and 94.02±6.87%, ranging from 77.78% to 100.0% for the recommended replacement group. The final weights recorded a mean of 57.70 ± 93.59 g, ranging from 3.43 to 361.89 g for the control group, and 64.29 ± 97.97 g, ranging from 5.22 to 374.08 g for the recommended replacement group. Weight gain was at a mean of 60.85 ± 111.07 g, ranging from 1.31 to 413.82 g for the control group, and 82.43 ± 174.37 g, ranging from 1.55 to 819.05 g for the recommended replacement group. SGR recorded a mean of 2.06 ± 1.13 g, ranging from 0.06 to 5.48 g for the control group, and 2.20 ± 1.17 g, ranging from 0.46 to 4.97 g for the recommended replacement group. FCR recorded a mean of 1.67 ± 0.80, ranging from 0.50 to 3.62 for the control group. At the same time, the mean FCR for the recommended replacement group was 1.54 ± 0.80 ranging from 0.50 to 4.18. Finally, a mean of 2.66 ± 4.74 was recorded for PER, ranging from 0.17 to 24.27 for the control group. Likewise, the recommended replacement group had a mean of 2.85 ± 4.70, ranging from 0.32 to 24.16.

Meta-Analysis

Analysis of the data gleaned from included studies was generally conducted for survival rate (1,448 samples), final weight (2,768 samples), weight gain (2,578 samples), SGR (3,548 samples), FCR (3,108 samples), and PER (3,108 samples). The outcome of the dichotomous analysis for survival rate revealed a non-significant effect of fishmeal replacement (OR = 1.28, 95% CI 0.86 to 1.89; $p > 0.05$; $I^2 = 0\%$) (Figure 2). Analyses of continuous data revealed that final weight (SMD = 5.43; 95% CI -2.72 to -1.45; $p < 0.001$; $I^2 = 99\%$) (Figure 3), weight gain (SMD = 5.59; 95% CI 4.08 to 7.10; $p < 0.001$; $I^2 = 99\%$) (Figure 4), SGR (SMD = 1.59; 95% CI 0.54 to 2.63; $p = 0.003$; $I^2 = 99\%$) (Figure 5), and PER (SMD = 2.54; 95% CI 1.68 to 3.40; $p < 0.001$; $I^2 = 99\%$) (Figure 6) revealed the significant effect of fishmeal replacement, while FCR (SMD = -0.24; 95% CI -0.21 to 0.81; $p = 0.61$; $I^2 = 99\%$) (Figure 7) establishing a non-significant overall effect of fish replacement in the diet of African catfish.

Analyses of continuous data for animal products revealed significant effects for the final weight (SMD = 4.86; 95% CI 1.73 to 7.99; $p = 0.002$; $I^2 = 99\%$) and weight gain (SMD = 3.07; 95% CI 1.07 to 5.07; $p = 0.003$; $I^2 = 99\%$), and non-significant effect for SGR (SMD = -0.14; 95% CI -1.64 to 1.36; $p = 0.86$; $I^2 = 99\%$) under the growth parameters. For the nutrient utilization parameters, a significant effect was recorded

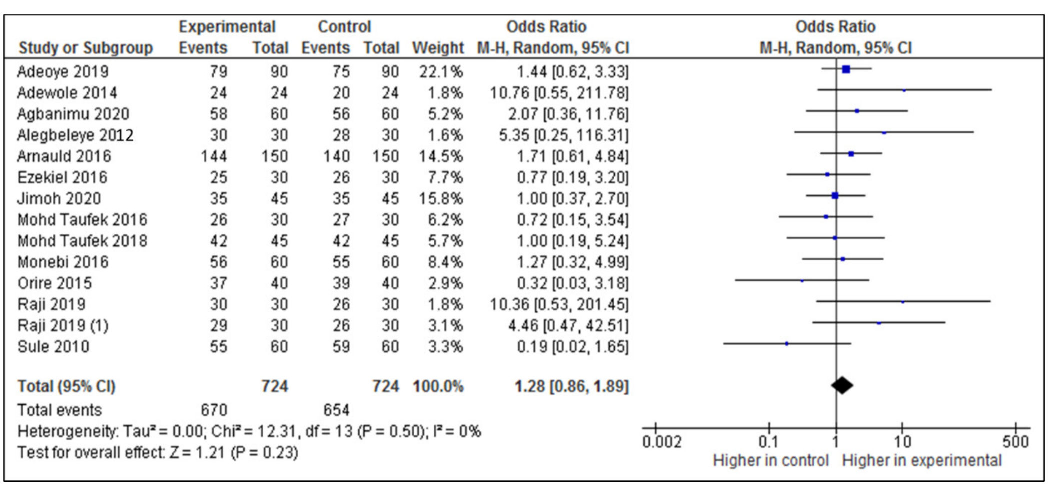

Figure 2. Forest plot of survival levels from different studies with recommended fishmeal replacement levels

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Adebayo 2017	16.35	0.34	30	15.71	0.3	30	4.5%	1.97 [1.35, 2.59]
Adeoye 2019	11.37	0.28	90	13.82	0.18	90	4.4%	-10.37 [-11.49, -9.24]
Aderolu 2009	48.69	2.73	100	31.25	2.08	100	4.5%	7.16 [6.40, 7.92]
Adesina 2021	16.84	0.17	40	14.54	0.2	40	4.2%	12.27 [10.27, 14.27]
Adewole 2014	66.5	13.44	24	78.92	2.71	24	4.5%	-1.26 [-1.88, -0.64]
Adewolu 2010	9.34	0.13	30	10	0.12	30	4.4%	-5.21 [-6.30, -4.12]
Agbanimu 2020	67.79	2.37	60	47.33	6.22	60	4.5%	4.32 [3.66, 4.98]
Alegbeleye 2012	5.75	0.27	30	4.74	0.51	30	4.5%	2.44 [1.76, 3.12]
Arnauld 2016	24.66	1.78	60	12.49	2.88	60	4.5%	5.05 [4.31, 5.79]
Ezekiel 2016	8.79	1.18	30	9.45	0.93	30	4.5%	-0.61 [-1.13, -0.09]
Huda 2020	5.22	0.14	75	4.69	0.28	75	4.5%	2.38 [1.96, 2.80]
Idowu 2017	9.75	0.5	20	9.55	3	20	4.5%	0.09 [-0.53, 0.71]
Jimoh 2020	16.95	0.73	45	24.2	1.58	45	4.4%	-5.84 [-6.81, -4.88]
Lawal 2017	199.7	10.06	20	138.1	21.58	20	4.4%	3.59 [2.55, 4.62]
Mamoon 2018	148.9	0.17	30	135.5	0.17	30	0.9%	77.80 [63.39, 92.21]
Mohd Taufek 2018	19.5	0.57	45	10.69	0.18	45	3.8%	20.67 [17.55, 23.78]
Monebi 2016	20	0.01	60	14.6	0.01	60	0.0%	536.56 [467.53, 605.59]
Nasser 2016	59.6	2.22	45	66.98	1.83	45	4.5%	-3.60 [-4.27, -2.92]
Nwanna 2004	32.8	0.1	150	32.8	0.1	150	4.5%	0.00 [-0.23, 0.23]
Ogunji 2020	47.17	4.15	45	19.87	0.3	45	4.3%	9.20 [7.76, 10.63]
Ogunji 2020 (1)	32.68	1.09	45	19.87	0.3	45	4.0%	15.89 [13.48, 18.30]
Orire 2015	3.33	0.56	40	3.43	0.24	40	4.5%	-0.23 [-0.67, 0.21]
Raji 2018	371.01	0.05	45	361.89	0.03	45	0.2%	219.30 [186.54, 252.07]
Raji 2018 (1)	374.08	0.29	45	361.89	0.03	45	1.8%	58.62 [49.86, 67.39]
Raji 2019	23.52	0.03	30	19.29	0.03	30	0.3%	139.17 [113.40, 164.93]
Raji 2019 (1)	24.14	0.01	30	19.29	0.03	30	0.1%	214.08 [174.45, 253.71]
Sheikhlar 2017	105.91	7.42	90	104.13	7.25	90	4.5%	0.24 [-0.05, 0.53]
Yalew 2019	29.8	0.45	30	30.7	0.4	30	4.5%	-2.09 [-2.72, -1.45]
Total (95% CI)			**1384**			**1384**	**100.0%**	**5.43 [3.92, 6.94]**

Heterogeneity: Tau² = 13.16; Chi² = 3146.06, df = 27 (P < 0.00001); I² = 99%
Test for overall effect: Z = 7.06 (P < 0.00001)

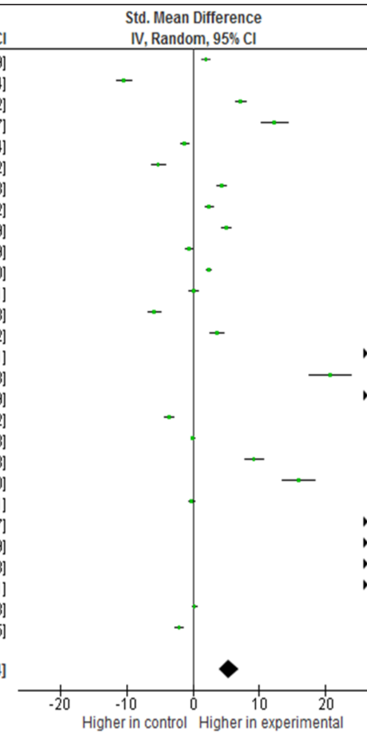

Figure 3. Forest plot of final weight from different studies with recommended fishmeal replacement levels

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Adebayo 2017	12.8	0.34	30	11.17	0.22	30	4.4%	5.62 [4.46, 6.77]
Aderolu 2009	39.04	2.07	100	20.75	1.78	100	4.5%	9.44 [8.46, 10.41]
Adesina 2021	11.73	0.02	40	9.42	0.21	40	4.1%	15.34 [12.86, 17.81]
Adewole 2014	57.68	10.52	24	68.07	2.7	24	4.5%	-1.33 [-1.96, -0.70]
Adewolu 2010	6.35	0.12	30	6.69	0.17	30	4.5%	-2.28 [-2.94, -1.62]
Agbanimu 2020	1.55	0.03	60	1.31	0.08	60	4.5%	3.95 [3.33, 4.57]
Arnauld 2016	819.05	63.04	150	413.82	95.22	150	4.5%	5.01 [4.54, 5.47]
Ezekiel 2016	5.14	1.18	30	5.95	0.95	30	4.5%	-0.75 [-1.27, -0.22]
Idowu 2017	5.58	1.4	20	4.79	2.2	20	4.5%	0.42 [-0.21, 1.05]
Jimoh 2020	11.25	0.74	45	18.46	1.62	45	4.5%	-5.68 [-6.62, -4.73]
Lawal 2017	160.42	11.98	20	103.92	21.5	20	4.5%	3.18 [2.22, 4.14]
Mamoon 2018	92.82	0.34	30	79.74	0.34	30	2.3%	37.97 [30.92, 45.02]
Mohd Taufek 2016	30.63	1.36	30	35.7	5.18	30	4.5%	-1.32 [-1.88, -0.76]
Mohd Taufek 2018	14.68	0.78	45	6.23	0.25	45	4.2%	14.46 [12.26, 16.66]
Monebi 2016	18.9	0.01	60	13.5	0.02	60	0.1%	339.35 [295.69, 383.01]
Nasser 2016	50.67	1.11	45	56.56	1.14	45	4.5%	-5.19 [-6.07, -4.31]
Nwanna 2004	20.7	0.1	150	20.6	0.17	150	4.6%	0.72 [0.48, 0.95]
Ogunji 2020	40.64	4.23	45	7.5	2.46	45	4.4%	9.50 [8.02, 10.97]
Ogunji 2020 (1)	24.29	1.84	45	7.5	2.46	45	4.4%	7.66 [6.45, 8.88]
Orire 2015	2.41	0.05	40	2.49	0.24	40	4.6%	-0.46 [-0.90, -0.01]
Raji 2018	328.96	2.31	45	319.78	0.02	45	4.5%	5.57 [4.64, 6.50]
Raji 2018 (1)	332.05	0.59	45	319.78	0.02	45	3.3%	29.14 [24.77, 33.52]
Raji 2019	15.67	0.01	30	11.7	0.03	30	0.2%	175.24 [142.80, 207.68]
Raji 2019 (1)	16.32	0.01	30	11.7	0.03	30	0.2%	203.93 [166.18, 241.68]
Sule 2010	21.47	1.16	60	22.59	1.43	60	4.6%	-0.85 [-1.23, -0.48]
Yalew 2019	2.41	0.05	40	2.49	0.24	40	4.6%	-0.46 [-0.90, -0.01]
Total (95% CI)			**1289**			**1289**	**100.0%**	**5.59 [4.08, 7.10]**

Heterogeneity: Tau² = 13.01; Chi² = 2881.09, df = 25 (P < 0.00001); I² = 99%
Test for overall effect: Z = 7.25 (P < 0.00001)

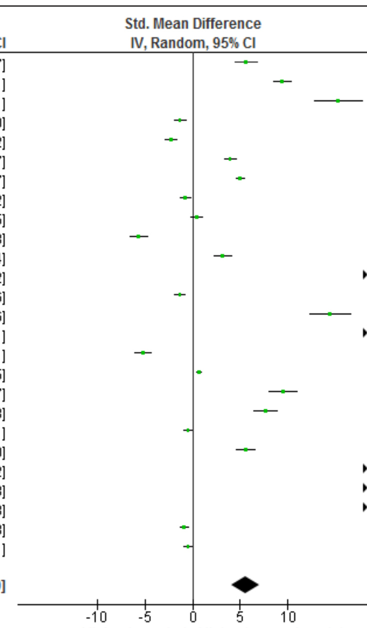

Figure 4. Forest plot showing the effect size for weight gain from different studies with recommended fishmeal replacement levels

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Adebayo 2017	1.69	0.06	30	1.54	0.03	30	3.3%	3.12 [2.35, 3.89]
Adeoye 2019	4.83	0.1	90	5.48	0.06	90	3.3%	-7.85 [-8.72, -6.98]
Aderolu 2009	2.42	0.82	100	1.61	0.07	100	3.3%	1.39 [1.08, 1.70]
Adesina 2021	2.13	0.23	40	1.86	0.11	40	3.3%	1.48 [0.99, 1.98]
Adewole 2014	1.03	0.07	24	0.06	0.14	24	3.0%	8.62 [6.73, 10.51]
Adewolu 2010	3.3	0.04	30	3.4	0.05	30	3.3%	-2.18 [-2.83, -1.53]
Agbanimu 2020	1.55	0.03	60	1.31	0.08	60	3.3%	3.95 [3.33, 4.57]
Alegbeleye 2012	2.64	0.06	30	2.5	0.16	30	3.3%	1.14 [0.60, 1.69]
Arnauld 2016	4.97	0.17	60	3.25	0.53	60	3.3%	4.34 [3.68, 5.01]
Ezekiel 2016	0.68	0.08	30	0.79	0.06	30	3.3%	-1.54 [-2.12, -0.96]
Huda 2020	1.31	0.08	75	1.55	0.03	75	3.3%	-3.95 [-4.51, -3.40]
Idowu 2017	0.7	0.2	20	0.5	0.1	20	3.3%	1.24 [0.56, 1.92]
Jimoh 2020	1.94	0.08	45	2.57	0.13	45	3.3%	-5.79 [-6.75, -4.83]
Lawal 2017	1.01	0.06	20	0.86	0.1	20	3.3%	1.78 [1.04, 2.53]
Mamoon 2018	1.08	0.01	30	1.05	0.01	30	3.3%	2.96 [2.22, 3.71]
Mohd Taufek 2016	2.63	0.1	30	2.76	0.2	30	3.3%	-0.81 [-1.34, -0.28]
Mohd Taufek 2018	2.32	0.15	45	1.49	0.1	45	3.2%	6.46 [5.41, 7.50]
Monebi 2016	1.4	0.02	60	1.27	0.01	60	3.2%	8.17 [7.06, 9.28]
Nasser 2016	2.71	0.05	45	2.66	0.08	45	3.3%	0.74 [0.32, 1.17]
Nwanna 2004	1.19	0.01	150	1.18	0.01	150	3.3%	1.00 [0.76, 1.24]
Ogunji 2020	3.3	0.19	45	1.66	0.42	45	3.3%	4.99 [4.14, 5.84]
Ogunji 2020 (1)	0.46	0.02	45	1.66	0.42	45	3.3%	-4.00 [-4.73, -3.27]
Orire 2015	2.29	0.17	40	2.22	0.76	40	3.3%	0.13 [-0.31, 0.56]
Raji 2018	2.58	0.01	45	2.56	0.01	45	3.3%	1.98 [1.47, 2.49]
Raji 2018 (1)	2.58	0.01	45	2.56	0.01	45	3.3%	1.98 [1.47, 2.49]
Raji 2019	3.12	0.01	30	2.92	0.01	30	2.4%	19.74 [16.05, 23.43]
Raji 2019 (1)	3.15	0.01	30	2.92	0.01	30	2.2%	22.70 [18.47, 26.93]
Rapatsa 2019	1.68	0.013	300	1.85	0.025	300	3.3%	-8.52 [-9.03, -8.01]
Sheikhlar 2017	4.24	0.21	90	4.22	0.35	90	3.3%	0.07 [-0.22, 0.36]
Sule 2010	0.87	0.1	60	0.91	0.13	60	3.3%	-0.34 [-0.70, 0.02]
Yalew 2019	2.53	0.2	30	2.6	0.1	30	3.3%	-0.44 [-0.95, 0.08]
Total (95% CI)			**1774**			**1774**	**100.0%**	**1.59 [0.54, 2.63]**

Heterogeneity: Tau² = 8.47; Chi² = 3466.02, df = 30 (P < 0.00001); I² = 99%
Test for overall effect: Z = 2.98 (P = 0.003)

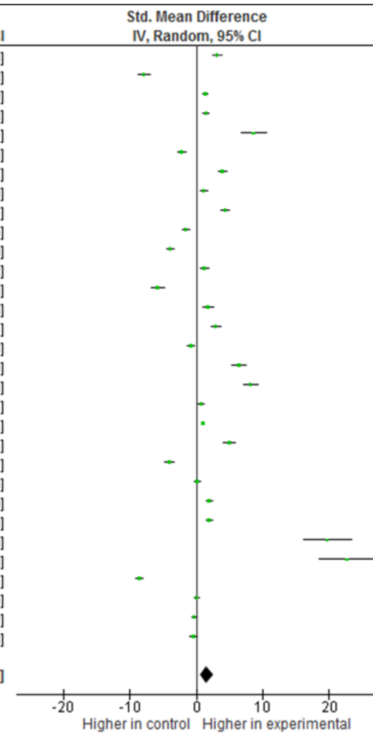

Figure 5. Forest plot of specific growth rates from different studies with recommended fishmeal replacement levels

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Adebayo 2017	1.35	0.02	30	1.39	0.03	30	4.1%	-1.55 [-2.13, -0.97]
Adeoye 2019	1.29	0.05	90	1.22	0.1	90	4.2%	0.88 [0.58, 1.19]
Aderolu 2009	2.05	0.19	100	2.29	0.24	100	4.2%	-1.10 [-1.40, -0.81]
Adesina 2021	0.5	0.11	40	0.5	0.1	40	4.2%	0.00 [-0.44, 0.44]
Adewole 2014	0.86	0.12	24	0.94	0.32	24	4.1%	-0.33 [-0.90, 0.24]
Adewolu 2010	1.44	0.03	30	1.34	0.06	30	4.1%	2.08 [1.44, 2.72]
Alegbeleye 2012	1.46	0.03	60	1.51	0.02	60	4.2%	-1.95 [-2.39, -1.51]
Arnauld 2016	1.06	0.02	30	2.03	0.43	30	4.1%	-3.15 [-3.92, -2.37]
Ezekiel 2016	4.18	0.48	30	3.62	0.98	30	4.1%	0.72 [0.19, 1.24]
Jimoh 2020	2.14	0.22	45	1.61	0.1	45	4.1%	3.08 [2.46, 3.69]
Mamoon 2018	2.06	0.01	30	2.11	0.01	30	4.0%	-4.94 [-5.98, -3.89]
Mohd Taufek 2016	1.24	0.05	45	1.17	0.2	45	4.2%	0.48 [0.06, 0.90]
Mohd Taufek 2018	2.2	0.17	45	3.5	0.82	45	4.1%	-2.18 [-2.70, -1.65]
Nasser 2016	0.78	0.06	45	0.74	0.07	45	4.2%	0.61 [0.19, 1.03]
Nwanna 2004	2.5	0.01	150	2.51	0.01	150	4.2%	-1.00 [-1.24, -0.76]
Ogunji 2020	1.41	0.13	45	1.97	0.09	45	4.0%	-4.97 [-5.82, -4.12]
Ogunji 2020 (1)	1.73	0.82	45	1.97	0.09	45	4.2%	-0.41 [-0.83, 0.01]
Orire 2015	1.24	0.81	40	1.29	0.5	40	4.2%	-0.07 [-0.51, 0.36]
Raji 2018	0.77	0.01	45	0.8	0.01	45	4.1%	-2.97 [-3.58, -2.37]
Raji 2018 (1)	0.77	0.01	45	0.8	0.01	45	4.1%	-2.97 [-3.58, -2.37]
Raji 2019	1.14	0.01	30	1.55	0.01	30	1.1%	-40.47 [-47.98, -32.96]
Raji 2019 (1)	0.93	0.01	30	1.55	0.01	30	0.6%	-61.19 [-72.53, -49.86]
Rapatsa 2019	1.26	0.001	300	1.22	0.001	300	3.3%	39.95 [37.68, 42.22]
Sheikhlar 2017	0.94	0.02	90	0.95	0.03	90	4.2%	-0.39 [-0.69, -0.10]
Sule 2010	2.08	0.03	60	2.06	0.03	60	4.2%	0.66 [0.29, 1.03]
Yalew 2019	2.73	0.1	30	2.7	0.1	30	4.1%	0.30 [-0.21, 0.81]
Total (95% CI)			**1554**			**1554**	**100.0%**	**-0.24 [-1.15, 0.68]**

Heterogeneity: Tau² = 5.17; Chi² = 2300.67, df = 25 (P < 0.00001); I² = 99%
Test for overall effect: Z = 0.51 (P = 0.61)

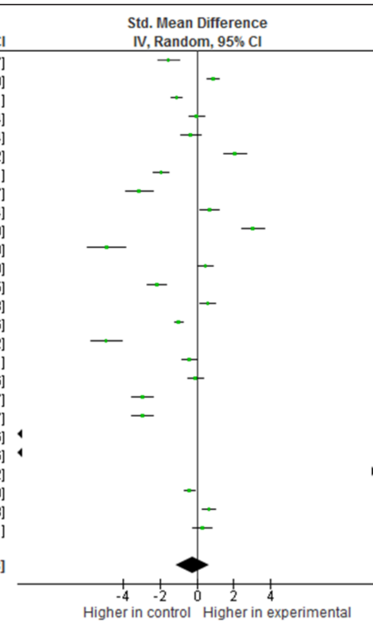

Figure 6. Forest plot of feed conversion ratio from different studies with recommended fishmeal replacement levels

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Adebayo 2017	0.33	0.08	30	0.24	0.05	30	4.6%	1.33 [0.77, 1.89]
Adeoye 2019	1.41	0.07	90	1.55	0.2	90	4.6%	-0.93 [-1.24, -0.62]
Aderolu 2009	1.34	0.05	100	1.15	0.04	100	4.6%	4.18 [3.68, 4.68]
Adesina 2021	5.57	0.15	40	4.96	0.43	40	4.6%	1.88 [1.35, 2.41]
Adewole 2014	0.32	0.01	24	0.17	0.04	24	4.3%	5.06 [3.86, 6.26]
Agbanimu 2020	1.41	0.07	90	1.55	0.2	90	4.6%	-0.93 [-1.24, -0.62]
Alegbeleye 2012	2.37	0.05	60	2.25	0.06	60	4.6%	2.16 [1.71, 2.61]
Arnauld 2016	2.35	0.03	30	1.16	0.16	30	3.8%	10.20 [8.25, 12.16]
Jimoh 2020	1.2	0.14	45	1.56	0.01	45	4.5%	-3.60 [-4.27, -2.92]
Mamoon 2018	1.05	0.01	30	1.03	0.01	30	4.5%	1.97 [1.35, 2.60]
Mohd Taufek 2016	2.3	0.1	45	2.56	0.38	45	4.6%	-0.93 [-1.36, -0.49]
Mohd Taufek 2018	1.69	0.17	45	1.11	0.08	45	4.5%	4.33 [3.56, 5.10]
Nasser 2016	3.68	0.07	45	3.87	0.09	45	4.6%	-2.34 [-2.88, -1.80]
Nwanna 2004	0.52	0.03	150	0.52	0.02	150	4.6%	0.00 [-0.23, 0.23]
Ogunji 2020	1.77	0.18	45	1.17	0.05	45	4.5%	4.50 [3.71, 5.29]
Ogunji 2020 (1)	1.43	0.07	45	1.17	0.05	45	4.5%	4.24 [3.48, 4.99]
Orire 2015	0.81	0.01	40	0.78	0.01	40	4.5%	2.97 [2.33, 3.62]
Raji 2018	3.11	0.02	45	3.03	0.01	45	4.5%	5.02 [4.16, 5.87]
Raji 2018 (1)	3.11	0.01	45	3.03	0.01	45	4.2%	7.93 [6.68, 9.19]
Raji 2019	1.92	0.01	30	1.35	0.01	30	0.6%	56.26 [45.83, 66.69]
Raji 2019 (1)	2.33	0.01	30	1.35	0.01	30	0.2%	96.73 [78.82, 114.64]
Rapatsa 2019	24.16	1.13	300	25.27	1.7	300	4.7%	-0.77 [-0.93, -0.60]
Sheikhlar 2017	2.74	0.11	90	2.75	0.1	90	4.6%	-0.09 [-0.39, 0.20]
Sule 2010	1.24	0.1	60	1.21	0.06	60	4.6%	0.36 [0.00, 0.72]
Total (95% CI)			**1554**			**1554**	**100.0%**	**2.54 [1.68, 3.40]**

Heterogeneity: Tau² = 4.17; Chi² = 1934.65, df = 23 (P < 0.00001); I² = 99%
Test for overall effect: Z = 5.76 (P < 0.00001)

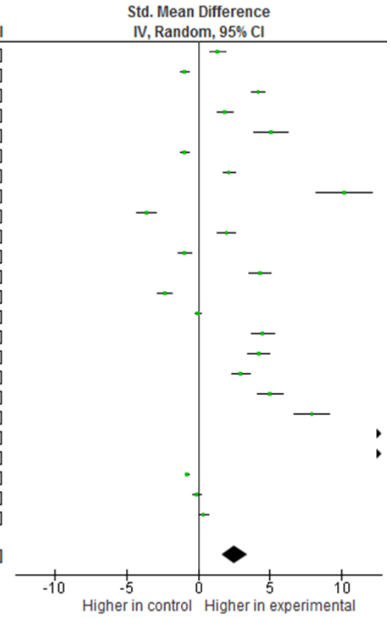

Figure 7. Forest plot of protein efficiency ratio from different studies with recommended fishmeal replacement level

for PER (SMD = 1.75; 95% CI 0.12 to 3.39; $p = 0.04$; $I^2 = 99\%$), while a non-significant effect was recorded for FCR (SMD = -0.69; 95% CI -2.00 to 0.63; $p = 0.31$; $I^2 = 98\%$) (Supplementary materials 1–2).

Analyses of continuous data for insects/worms revealed significant effects for the final weight (SMD = 5.74; 95% CI 1.60 to 9.88; $p = 0.007$; $I^2 = 99\%$) and weight gain (SMD = 9.23; 95% CI 4.45 to 14.00; $p < 0.001$; $I^2 = 99\%$), and non-significant effect for SGR (SMD = 0.32; 95% CI -9.03 to -8.01; $p = 0.86$; $I^2 = 100\%$) under the growth parameters. For the nutrient utilization parameters, a significant effect was recorded for PER (SMD = 1.50; 95% CI 0.32 to 2.67; $p = 0.01$; $I^2 = 99\%$), while a non-significant effect was recorded for FCR (SMD = -1.16; 95% CI -2.67 to 0.35; $p = 0.13$; $I^2 = 98\%$) (Supplementary materials 3–4).

Analyses of continuous data for algae/plants revealed significant effects for the final weight (SMD = 6.14; 95% CI 4.11 to 8.16; $p < 0.001$; $I^2 = 99\%$), weight gain (SMD = 7.42; 95% CI 4.69 to 10.15; $p < 0.001$; $I^2 = 99\%$), and specific growth rate (SMD = 2.16; 95% CI 1.30 to 3.03; $p < 0.001$; $I^2 = 97\%$). For the nutrient utilization parameters, a significant effect was recorded for FCR (SMD = -1.69; 95% CI -2.64 to 0.76; $p < 0.001$; $I^2 = 97\%$) and PER (SMD = 5.22; 95% CI 3.19 to 7.25; $p < 0.13$; $I^2 = 99\%$) (Supplementary materials 5-6).

DISCUSSION

To assess the potential of partially or wholly replacing fishmeal in the diet of an important aquaculture species, the African catfish, this review systematically selected and analyzed previous research publications based on predetermined criteria. The focus on African catfish was to provide specific information regarding the performance of various alternative protein sources. Consequently, this review considered not only a higher number of studies but individuals of African catfish for the analyses of growth and nutrient utilization parameters compared to Luthada-Raswiswi et al. (2021). The latter reviewed the replacement of fish meal in various fish species.

The highest recommended fishmeal replacement level for animal products in the diet of African catfish did not exceed 50% for a blood meal and bovine rumen blend. The lowest was as low as 7% for bloodmeal, as opposed to insects/worms and plant products, which replaced as much as 75 to 100% of fishmeal at recommended levels. The limitation of using purely blood-based ingredients in the diet of African catfish is established due to the decline experienced with an increase in blood meal inclusion (Ogunji et al., 2020). Like its level of inclusion in the diet of African catfish, blood meal had been reportedly included at 6% to 10% in the diets of grouper *Epinephelus coioides* (Martins & Guzman, 1994), juvenile trout *Oncorhynchus mykiss* (Martins & Guzman, 1994), and gilthead sea bream *Sparus aurata* (Luzier et al., 1995).

Apart from Bambara nutmeal, spirulina, and *Chlorella* recorded the highest recommended replacement level in the algae/plant category and are the only algal taxa reported in the included studies. The performance and potential of algal species in the sustainable production of fish, especially African catfish, is revealed, making further research on the characteristics of this group of organisms quintessential. Microalgae have a high amount of protein with digestible amino acid profiles. Thus, they are equivalent to those found in other foods, such as antioxidants, sulfated polysaccharides, polyunsaturated fatty acids, β-carotene, and sterols (Raji et al., 2020; Reyes-Becerril et al., 2013). Sarker et al. (2020) reported the possibility of eliminating fish meal from the diet of Nile tilapia by replacing it with a microalgae blend. As a result, better protein quality, growth, and nutrient utilization parameters were reported. Besides, using microalgae could also help guarantee adherence to sustainability standards as it would reduce the dependence on wild fish, which are facing depletion due to overexploitation (Shah et al., 2018). Microalgae have also been noted to possess nutrient stability over a long period. For example, frozen microalgae-based aquafeed maintained stability for about nine months (Camacho-Rodríguez et al., 2018).

Ido et al. (2019) reported an improvement in growth performance and disease resistance of red sea bream *Pagrus major* when fishmeal was replaced with a yellow mealworm in its diet. However, according to Tilami et al. (2020), despite the potential for replacement of fish meal, some insects, such as house cricket *Acheta domesticus* and super worm *Zophobas morio*, in the diet of perch *Perca fluviatilis* negatively influenced its growth parameters.

The inclusion of insects may not give similar positive results in the diet of all fish species, indicating the need for more species-specific consideration in terms of insect inclusion. Insects are rich in amino acids, lipids, vitamins, and minerals (Pinotti et al., 2019). Also, their reproduction requires no arable land, energy, or water making their ecological footprint insignificant (Oonincx & de Boer, 2012). They have more natural reproduction with a faster development rate and convert low-quality organic materials into high-value proteins (Sánchez-Muros et al., 2014). Antifungal and antibacterial activities have also been reported for many insects, thereby improving the shelf-life of feeds containing them (Henry et al., 2015). However, the use of insects is not without limitations, such as low concentrations of sulfur-containing amino acids and varying nutritional value, depending on the species, stage of development, and substrate used to feed the insect.

Aqua feeds that result from the mixture of feed ingredients of different types may present a superior performance in the growth and nutrient utilization of African catfish and other fresh and marine water fish species. For example, the highest replacement level recorded in this review was achieved with a diet that stemmed from a mixture of two different animal products. This situation points to the possibility of achieving higher performance with blended animal products. More so, replacing fishmeal with insects/worms in the diet of African catfish appears to present the highest possible recommended replacement level. Again, one of the ingredients that recorded the highest possible recommended replacement level was blended earthworm and maggot meal, corroborating the possibility of recording better results when ingredients are blended or mixed to replace fishmeal as protein sources in fish species (Djissou et al., 2016).

Except for FCR, the experimental groups' growth and nutrient utilization parameters were higher at the recommended fish meal replacement levels. From this result, it could be deduced that fishmeal replacement at prescribed levels is undoubtedly more beneficial for African catfish growth and nutrient utilization. This situation is in line with the findings of Luthada-Raswiswi et al. (2021). They reported statistically significant differences in growth and nutrient utilization parameters based on a review of various fish species when the fish meal in their feeds was replaced. This review provides important information on the value of replacing fishmeal with other nutritive yet cheaper protein sources.

Meta-analysis corroborated the descriptive information and depicted the significant association between the recommended replacement levels versus growth and nutrient utilization parameters. Aside from survival level and FCR, all other parameters generally recorded a significant effect of fishmeal replacement. Again, it could be deduced that fishmeal replacement at prescribed levels is undoubtedly more beneficial for African catfish growth and nutrient utilization. As opposed to other categories, all the growth and nutrient utilization parameters in the algae/plant category revealed a significant effect of fish meal replacement. Feed ingredients of plant origin, especially the microalgae followed by insects/worms, need to be researched in greater detail for African catfish and many other aquaculture species of commercial importance.

Generally, the level of heterogeneity in the included studies was high. The size, inclusion levels, and recommended protein levels were reported, which are the likely reasons our meta-analysis indicated heterogeneity in studies. Despite the heterogeneity observed, these animal protein sources have positively affected FCR, SGR, final weight, and survival of different fish species of varying size groups.

CONCLUSION

Based on their significant general effects on African catfish's growth and nutrient utilization parameters at higher recommended inclusion levels, feed ingredients of plant origin, especially the microalgae followed by insects/worms, are highly promising. Therefore, they need to be researched in greater detail for African catfish and many other aquaculture species of commercial importance. In addition, mixing ingredients at tested proportions to replace fishmeal may produce a better outcome. However, compared to single components usage for replacement, there seems to be a shortage of research in this regard. Therefore, systematic reviews and meta-analyses of studies regarding replacing fish meals with other protein sources should be approached more specifically on a species basis. This analysis will provide greater insights and guidance toward increasing fish production at reduced costs and contributing to global food security.

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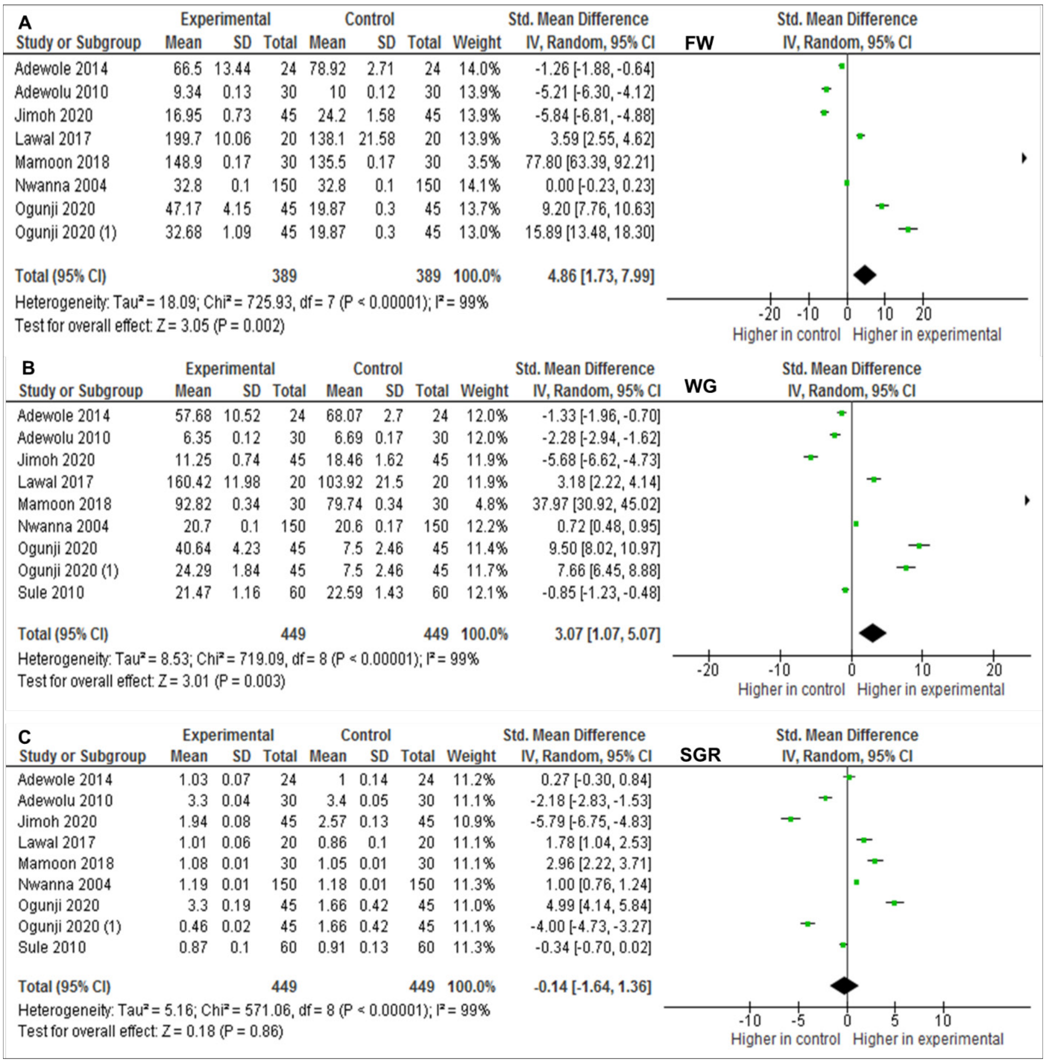
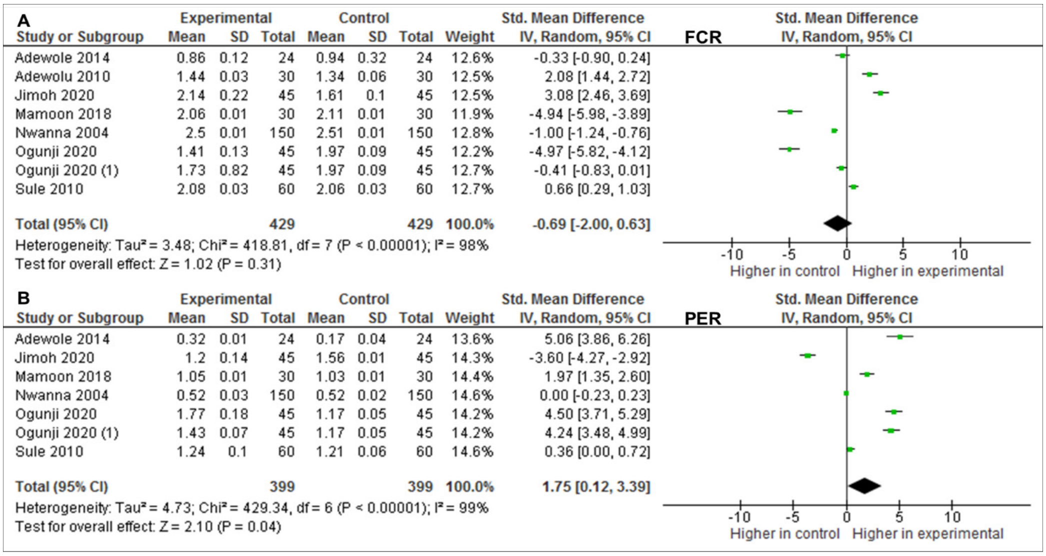
APPENDICES



Supplementary material 1. Forest plot showing the effect sizes of growth parameters for fishmeal replacement with animal products in African catfish



A — FCR

Study or Subgroup	Experimental Mean	SD	Total	Control Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
Adewole 2014	0.86	0.12	24	0.94	0.32	24	12.6%	-0.33 [-0.90, 0.24]
Adewolu 2010	1.44	0.03	30	1.34	0.06	30	12.5%	2.08 [1.44, 2.72]
Jimoh 2020	2.14	0.22	45	1.61	0.1	45	12.5%	3.08 [2.46, 3.69]
Mamoon 2018	2.06	0.01	30	2.11	0.01	30	11.9%	-4.94 [-5.98, -3.89]
Nwanna 2004	2.5	0.01	150	2.51	0.01	150	12.8%	-1.00 [-1.24, -0.76]
Ogunji 2020	1.41	0.13	45	1.97	0.09	45	12.2%	-4.97 [-5.82, -4.12]
Ogunji 2020 (1)	1.73	0.82	45	1.97	0.09	45	12.7%	-0.41 [-0.83, 0.01]
Sule 2010	2.08	0.03	60	2.06	0.03	60	12.7%	0.66 [0.29, 1.03]
Total (95% CI)			**429**			**429**	**100.0%**	**-0.69 [-2.00, 0.63]**

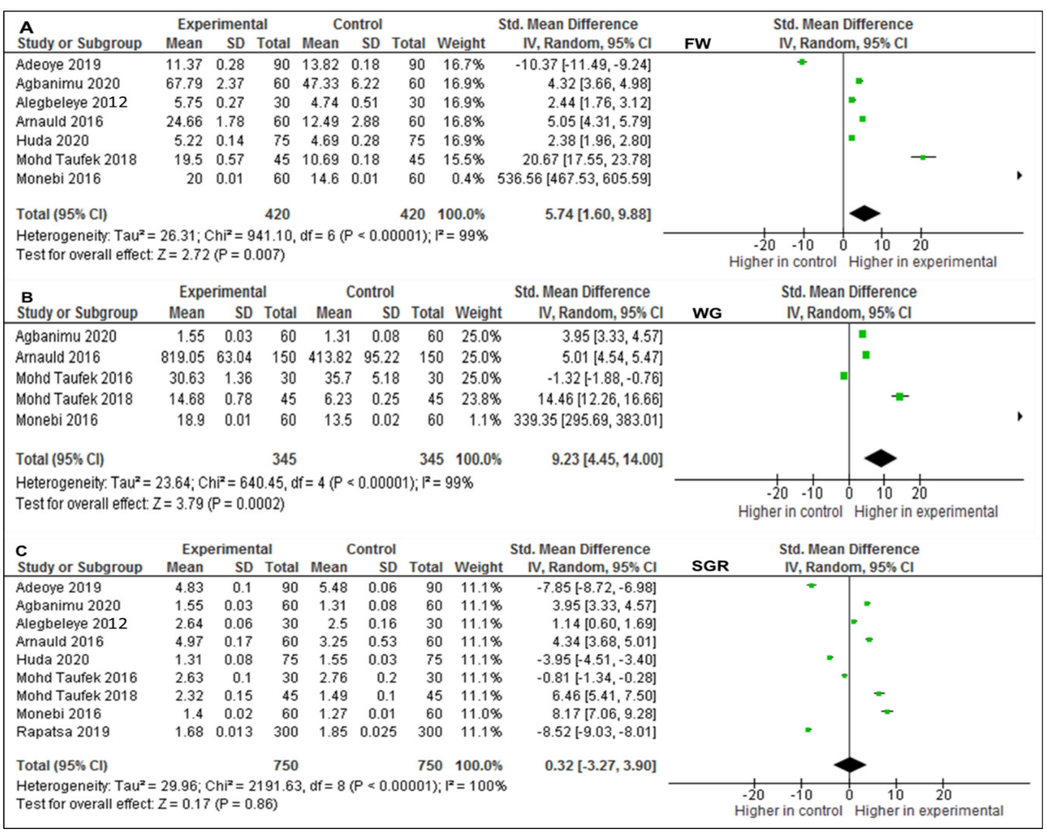
Heterogeneity: Tau² = 3.48; Chi² = 418.81, df = 7 (P < 0.00001); I² = 98%
Test for overall effect: Z = 1.02 (P = 0.31)

B — PER

Study or Subgroup	Experimental Mean	SD	Total	Control Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
Adewole 2014	0.32	0.01	24	0.17	0.04	24	13.6%	5.06 [3.86, 6.26]
Jimoh 2020	1.2	0.14	45	1.56	0.01	45	14.3%	-3.60 [-4.27, -2.92]
Mamoon 2018	1.05	0.01	30	1.03	0.01	30	14.4%	1.97 [1.35, 2.60]
Nwanna 2004	0.52	0.03	150	0.52	0.02	150	14.6%	0.00 [-0.23, 0.23]
Ogunji 2020	1.77	0.18	45	1.17	0.05	45	14.2%	4.50 [3.71, 5.29]
Ogunji 2020 (1)	1.43	0.07	45	1.17	0.05	45	14.2%	4.24 [3.48, 4.99]
Sule 2010	1.24	0.1	60	1.21	0.06	60	14.6%	0.36 [0.00, 0.72]
Total (95% CI)			**399**			**399**	**100.0%**	**1.75 [0.12, 3.39]**

Heterogeneity: Tau² = 4.73; Chi² = 429.34, df = 6 (P < 0.00001); I² = 99%
Test for overall effect: Z = 2.10 (P = 0.04)

Supplementary material 2. Forest plot showing the effect sizes of nutrient utilization parameters after recommended fishmeal replacement with animal products in African catfish



A — FW

Study or Subgroup	Experimental Mean	SD	Total	Control Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
Adeoye 2019	11.37	0.28	90	13.82	0.18	90	16.7%	-10.37 [-11.49, -9.24]
Agbanimu 2020	67.79	2.37	60	47.33	6.22	60	16.9%	4.32 [3.66, 4.98]
Alegbeleye 2012	5.75	0.27	30	4.74	0.51	30	16.9%	2.44 [1.76, 3.12]
Arnauld 2016	24.66	1.78	60	12.49	2.88	60	16.8%	5.05 [4.31, 5.79]
Huda 2020	5.22	0.14	75	4.69	0.28	75	16.9%	2.38 [1.96, 2.80]
Mohd Taufek 2018	19.5	0.57	45	10.69	0.18	45	15.5%	20.67 [17.55, 23.78]
Monebi 2016	20	0.01	60	14.6	0.01	60	0.4%	536.56 [467.53, 605.59]
Total (95% CI)			**420**			**420**	**100.0%**	**5.74 [1.60, 9.88]**

Heterogeneity: Tau² = 26.31; Chi² = 941.10, df = 6 (P < 0.00001); I² = 99%
Test for overall effect: Z = 2.72 (P = 0.007)

B — WG

Study or Subgroup	Experimental Mean	SD	Total	Control Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
Agbanimu 2020	1.55	0.03	60	1.31	0.08	60	25.0%	3.95 [3.33, 4.57]
Arnauld 2016	819.05	63.04	150	413.82	95.22	150	25.0%	5.01 [4.54, 5.47]
Mohd Taufek 2016	30.63	1.36	30	35.7	5.18	30	25.0%	-1.32 [-1.88, -0.76]
Mohd Taufek 2018	14.68	0.78	45	6.23	0.25	45	23.8%	14.46 [12.26, 16.66]
Monebi 2016	18.9	0.01	60	13.5	0.02	60	1.1%	339.35 [295.69, 383.01]
Total (95% CI)			**345**			**345**	**100.0%**	**9.23 [4.45, 14.00]**

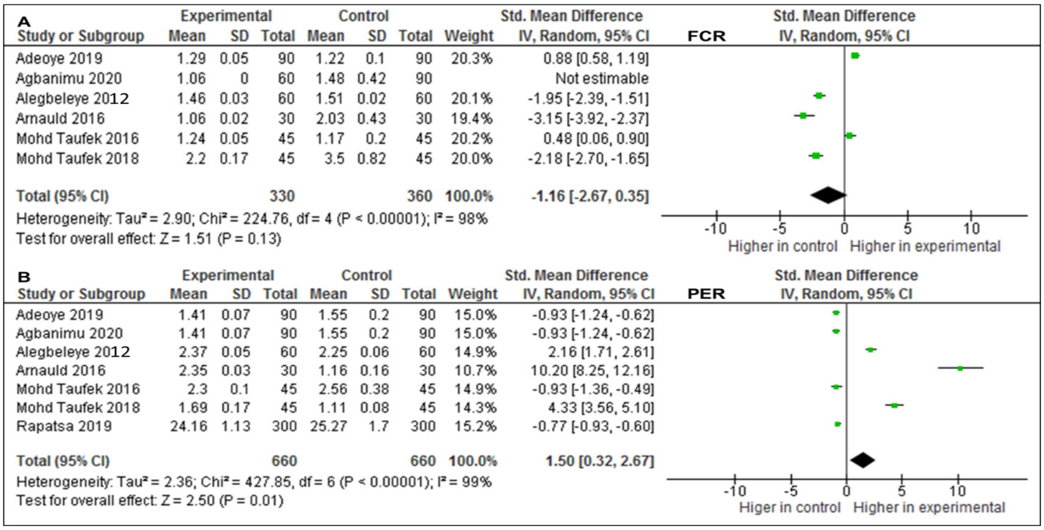
Heterogeneity: Tau² = 23.64; Chi² = 640.45, df = 4 (P < 0.00001); I² = 99%
Test for overall effect: Z = 3.79 (P = 0.0002)

C — SGR

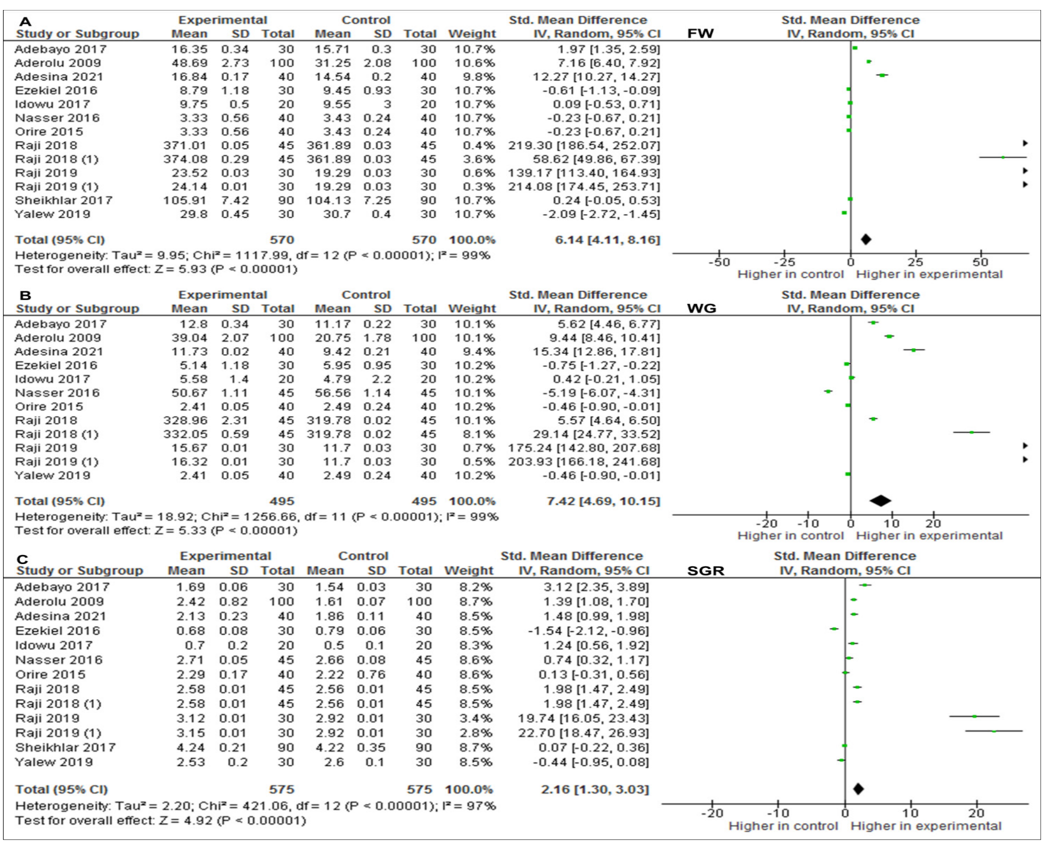
Study or Subgroup	Experimental Mean	SD	Total	Control Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
Adeoye 2019	4.83	0.1	90	5.48	0.06	90	11.1%	-7.85 [-8.72, -6.98]
Agbanimu 2020	1.55	0.03	60	1.31	0.08	60	11.1%	3.95 [3.33, 4.57]
Alegbeleye 2012	2.64	0.06	30	2.5	0.16	30	11.1%	1.14 [0.60, 1.69]
Arnauld 2016	4.97	0.17	60	3.25	0.53	60	11.1%	4.34 [3.68, 5.01]
Huda 2020	1.31	0.08	75	1.55	0.03	75	11.1%	-3.95 [-4.51, -3.40]
Mohd Taufek 2016	2.63	0.1	30	2.76	0.2	30	11.1%	-0.81 [-1.34, -0.28]
Mohd Taufek 2018	2.32	0.15	45	1.49	0.1	45	11.1%	6.46 [5.41, 7.50]
Monebi 2016	1.4	0.02	60	1.27	0.01	60	11.0%	8.17 [7.06, 9.28]
Rapatsa 2019	1.68	0.013	300	1.85	0.025	300	11.1%	-8.52 [-9.03, -8.01]
Total (95% CI)			**750**			**750**	**100.0%**	**0.32 [-3.27, 3.90]**

Heterogeneity: Tau² = 29.96; Chi² = 2191.63, df = 8 (P < 0.00001); I² = 100%
Test for overall effect: Z = 0.17 (P = 0.86)

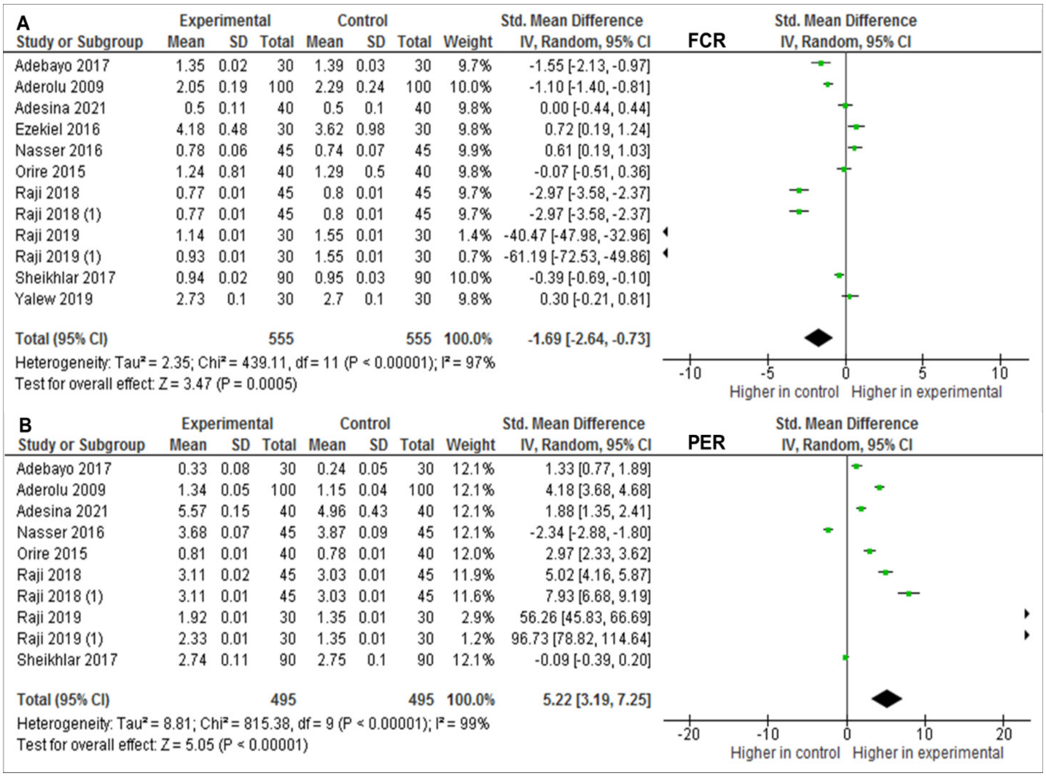
Supplementary material 3. Forest plot showing the effect sizes of growth parameters for fishmeal replacement with insects/worms in African catfish



Supplementary material 4. Forest plot showing the effect sizes of nutrient utilization based on fishmeal replacement with insects/worms in African catfish



Supplementary material 5. Forest plot showing the effect sizes of growth parameters for fishmeal replacement with algae/plants in African catfish



Supplementary material 6. Forest plot showing the effect sizes of nutrient utilization parameters for fishmeal replacement with algae/plants in African catfish