Aquaculture International (2025) 33:454
https://doi.org/10.1007/s10499-025-02135-0

REVIEW

Update on terrestrial and aquatic worms of the subclass oligochaeta in larviculture and aquaculture nutrition: biomass production, benefits, potential risks, and management strategies

Muziri Mugwanya[1] · **Mahmoud A. O. Dawood**[1] · **Hani Sewilam**[1,2]

Received: 22 May 2025 / Accepted: 7 July 2025

Abstract

Annelids of the subclass oligochaeta are among the most cost-effective live feeds in larviculture and aquaculture nutrition due to their balanced nutrient profile and ease of culture. Their inclusion in larviculture and aquaculture diets in different forms, such as live feed and frozen or processed forms, makes them feasible feed supplements in sustainable aquaculture production. As such, this review aims to discuss their biomass production, benefits, potential risks, management challenges, and strategies. The first part of the review gives a brief overview of the significance of live feeds in larviculture and the aquaculture industry, and the second part discusses what we know about the different culture substrates used in the mass production of commonly researched oligochaetes, *Tubifex* sp. (sludge worms), *Eisenia fetida*. (earthworms), and *Enchytraeus albidus* (white worms), and their influence on oligochaete nutrient profile. Information on their essential amino acid profiles is given and compared to the dietary requirements of two important fish species, *Oreochromis niloticus* and *Clarias gariepinus*. The third part of the review delves into the influence of oligochaete dietary supplementation on fish growth performance, non-specific immunity, and flesh quality. Part four summarizes the associated potential risks in the mass production of oligochaetes, such as pathogen, parasite, and prion transmission, emergence of antibiotic resistance genes, and bioaccumulation of hazardous pesticides in cultured oligochaetes. Lastly, management strategies and future research perspectives are discussed. The information given in this review will guide aquaculture farmers on safe and sustainable culture practices aimed at improving the biomass production and nutrient profile of oligochaetes.

Keywords Annelida · Aquafeed · Nutrition · Growth performance · Immunity · Sustainability

Handling Editor: Marco Saroglia

Extended author information available on the last page of the article

Published online: 22 July 2025

Introduction

Nutrition plays a significant role in the success of commercial larviculture and aquaculture (Hoseinifar et al. 2023; Lahnsteiner et al. 2023; McKay and Jeffs 2023; Truong et al. 2023). Growth performance parameters (i.e., specific growth rate (SGR), feed conversion ratio (FCR), protein efficiency ratio (PER), condition factor, and survival) and health of several aquaculture species reared have been linked to the nutritional quality, acceptance, and digestibility of the administered feed (Thongprajukaew et al. 2013; Devic et al. 2018; Ansari et al. 2021). As such, the poor growth performance of several aquaculture species has been partly attributed to the replacement of fish meal (FM) with other feed ingredients of lower nutritional composition that do not meet the dietary requirements of the species (Hussain et al. 2018; Gupta et al. 2020; Wang et al. 2020). Furthermore, the introduction of formulated dry feed in diets of different species of fish and shellfish larvae has been previously reported to hinder critical stages of larval development, leading to increased larval mortalities (Cahu and Infante 2001; Hamre et al. 2013; McKay and Jeffs 2022). For the past three decades, several countries have explored the feasibility and sustainability of supplementing aquaculture diets with highly nutritious worms to lower the cost of production. Among these feed alternatives, worms belonging to the subclass oligochaeta have shown great potential due to their rich nutrient composition in terms of crude protein, amino acids, vitamins, minerals, and polyunsaturated fatty acids content that are essential for the proper growth and development of fish and shellfish (Lietz 1987; Kolesnyk et al. 2019; Musyoka et al. 2019). As such, they are competitive alternatives to others, such as squid meal, krill meal, and mussel meal, which contain similar or even higher percentages of macronutrients that are within the dietary requirements of several aquaculture species (Derby et al. 2016; Novriadi et al. 2017; Saleh et al. 2018; Sicuro et al. 2023). It is worth noting that these worms (oligochaetes) are cosmopolitan and thrive well in wild and or/polluted environments (i.e., trenches, gutters, drains, ponds, rivers, agricultural soils, and sludge) and have been traditionally collected from the wild to be used as bait in capture fisheries (Kolesnyk et al. 2019). However, the mass production of these worms in different culture media substrates has an impact on their nutrient composition, hence offering a viable alternative to supplement aquaculture diets.

In this review, we report on the three most commonly studied worm species belonging to the subclass Oligochaeta (i.e., *Tubifex* sp., *Eisenia fetida*, and *Enchytraeus albidus*), their culture substrates, nutrient profile, and the influence of their dietary supplementation in larviculture and aquaculture nutrition on several growth performance parameters, flesh quality, and immune responses. Potential risks and production challenges are highlighted, and future research perspectives have been suggested for sustainable larviculture and aquaculture production.

Culture substrates and nutrient profile of oligochaetes

Culture media substrates for Tubifex sp., Eisenia fetida, and Enchytraeus albidus mass production

Tubifex sp., *Eisenia fetida*., and *Enchytraeus albidus* are the most studied worms of the subclass oligochaeta for their role in aquaculture nutrition. This is due to their easy culture using different organic substrates, adaptability to various environments, and high protein content. Tables 1, 2, and 3 summarize the growth and yield response of *Tubifex* sp., *E. fetida*, and *E. albidus*, respectively, as affected by different culture media substrates. Their ability to grow and reproduce on organic matter wastes alone (such as cow dung, coffee husks, sludge, slurry, wheat bran, wheat straw, farm yard manure, and poultry manure) or in combination with different quantities of other animal feed ingredients (such as soybean meal, mustard oil cake, and fish feed) has prompted scientists to explore the effect of different combinations of culture substrates on the nutrient composition, fecundity, and biomass yield of worms (Gunadi et al. 2002; Hossain et al. 2012; Begum et al. 2014; Fairchild et al. 2017; Hasan et al. 2019; Mashur et al. 2021; Haque and Hasan 2022; Belmeskine et al. 2023). For instance, Mandal et al. (2016) investigated the influence of different agro-industrial wastes (rice mill sludge (RMS) and dairy sludge (DS)) and raw cattle dung (RCD) on the protein and lipid composition of *Tubifex tubifex* worms. The authors observed high crude protein contents of 28.81% (6.38%, wet basis) and 27.44% (5.87% wet basis) in the carcass of worms cultured in RMS and DS, compared to those reared in RCD. Likewise, higher crude lipid contents of 13.64% (3.02% wet basis) and 6.03% (1.29% wet basis) were detected in the carcass of worms cultured in RMS and DS, respectively, compared to those cultured in RCD. In another study, Herawati et al. (2016) fermented different animal wastes (goat manure, chicken manure, quail manure, tofu, and rejected bread) using probiotic bacteria and assessed their influence on the nutritional composition of tubifex worms. Their results indicated that a mixture of 50 g/L quail manure, 100 g/L rejected bread, and 50 g/L of tofu waste produced the highest protein (66.26%) and fat (12.79%) content. Hasan et al. (2019) elucidated the effect of wetting media (cattle blood, rice gruel, and water) of the culture media ingredients (a mixture of mustard oil cake, soybean meal, and mud) on the protein and amino acid content of tubifex worms. Their results suggested that worms cultured in cattle blood-wetting media exhibited the highest lysine, leucine, and arginine content. Moreover, the highest protein (58.20%) and fat (13.20%) contents were observed in the same wetting media. For *E. fetida*, Musyoka et al. (2020b) inoculated pre-composted matter of coffee husks (CH), barley wastes (BW), and kitchen wastes (KW) with *E. fetida* and vermicomposted it for 70 days under controlled environments. The authors observed a higher nutritional profile in terms of crude protein (57.53% and 51.03%) and crude lipids (3.80% and 5.57%) in worms cultured in BW and CH compared to those in KW. For *E. albidus*, Bahrioğlu et al. (2023) reported that culturing and feeding worms on a garden soil-fish feed-based diet and peat-fish feed-based diets yielded higher protein contents (57.44% and 57.13%) in worms. Fairchild et al. (2017) also observed that culturing and feeding *E. albidus* on mixed produce yielded higher protein contents, reaching up to 69%. In addition to the composition of the culture substrate and feed, other factors such as temperature, moisture content, water flow, oxygen concentration, and pH have a significant influence on the growth and survival of oligochaetes (Degefe and Tamire 2017).

Amino acid profile of oligochaetes and recommended requirements for Nile tilapia (*Oreochromis niloticus*) and the African catfish (*Clarias gariepinus*)

Although culture conditions influence the nutrient composition of oligochaetes, their amino acid profile remains essential for the proper growth and survival of fish (Musyoka et al. 2019, 2020a). They play a significant role in protein synthesis, regulating FI, cell signaling, immune response, and fish metabolism. Any deficiency in the essential amino acids will disrupt protein synthesis, leading to adverse effects. Hence, critical care should

Table 1 Summary of studies on different culture media substrates used to culture *Tubifex* sp

Culture media substrates	Observations	Reference
30% mustard oil cake, 30% soybean meal, and 30% mud combined with wetting agents such as cattle blood, rice gruel, and or subsurface clean water	Highly significant worm yields (683 mg cm^{-2}) were noted in culture media ingredients (30% mustard oil cake, 30% soybean meal, 30% mud) wetted with cattle blood. Higher amino acid concentrations of lysine, arginine, and leucine in worms were noted	Hasan et al. (2019)
Mustard oil cake wetted in cattle blood, rice gruel, and subsurface clean water	75 mg cm^{-2} media ingredients and 100 mg cm^{-2} worm inoculum were the best combination at the pilot scale level culture of *Tubifex* worms for 70 days	Haque and Hasan (2022)
Cow dung media (70% cow dung and 30% field soil), raw fish media (20% raw fish slice and 80% soil), and vegetables (70% blended vegetable matter of kitchen cabbage and 30% soil)	Providing the culture media ingredients at the rate of 250 mg cm^{-2} per week for 145 days led to improved growth and production (8.192 mg g^{-1}) of *Tubifex* worms fed on cow dung media	Begum et al. (2014)
Chicken manure, goat manure, quail manure, rejected bread, and tofu wastes fermented with probiotic microbes (*Saccharomyces cerevisiae* and *Lactobacillus* sp.)	Significant growth in terms of the dense population of Tubifex worms was observed in populations cultured in quail manure, rejected bread, and tofu waste. Likewise, the highest protein and fat were observed in the same media, respectively	Herawati et al. (2016)
20% wheat bran, 30% soybean meal, 20% mustard oil cake, 20% cow dung, and 10% sand	A harvest level of 50 mg cm^{-2} at 10-day intervals starting from 30 days of the worm's inoculation was found suitable for sustainable yield in the later sampling durations	Hossain et al. (2011)
20% wheat bran, 30% soybean meal, 20% mustard oil cake, 20% cow dung, 10% sand, and rice gruel	The highest yield of worms (1126.03 mg cm^{-2}) was obtained when rice gruel was used to wet the culture media ingredients	Hossain et al. (2012)
Rice mill sludge, dairy sludge, and raw cattle dung	*Tubifex* worms fed on rice mill sludge and dairy sludge exhibited higher protein and fat content. Efficiency on the production of g *Tubifex* per kg of waste material was highest at 10 days, declining with time for all waste materials	Mandal et al. (2016)
75% cow dung and 25% fine sand, continuous water flow	This culture media was suitable for the production of *Tubifex* worms, provided there is a continuous flow of water at the rate of 250 ml min^{-1} with an oxygen flow of 3 mg L^{-1}	Marian and Pandian (1984)
Treatment I (20% mustard oil cake, 35% wheat bran, 25% cow dung, 20% sand), Treatment II (25% mustard oil cake, 30% wheat bran, 25% cow dung, 20% sand), Treatment III (35% mustard oil cake, 20% wheat bean, 25% cow dung, 20% sand)	The highest yield (503.39 mg cm^{-2}) was observed on the 70th day of culture duration in treatment III. Likewise, inoculation of media at 10-day intervals showed significantly higher production of worms (488.94 mg cm^{-2})	Mollah et al. (2012)

Table 1 (continued)

Culture media substrates	Observations	Reference
TetraColor tropical flakes (Tetra Holding Inc, Blacksburg, Virginia), HBH Algae Grazers (HBH Pet Products, Springville, Utah), and cow manure	Poor growth performance was noted in worms fed on cow manure. However, better growth and recruitment were noted in worms fed on either Tetra tropical flakes or HBH Algae Grazers containing *Spirulina* spp.	Oplinger et al. (2011)
Pig dung, poultry excreta, and dairy sludge. Municipal wastewater was used for the circulation of experimental trenches	Maximum biomass (125.53 g) was observed in worms fed on poultry excreta, followed by pig dung (99.47 g), and dairy sludge (10.09 g)	Singh et al. (2010)
Treatment A (mud and soybean curd residue), Treatment B (mud and chicken manure), Treatment C (mud and pig manure), and Treatment D (control; mud only)	Worms cultured in treatment A exhibited the highest growth	Solang et al. (2014)
40% tofu dregs, 25% fish silage, 25% fine bran and 10% mustard greens with three substrate media doses (114 g m^{-2}, 228 g m^{-2}, and 324 g m^{-2})	Best growth performance was achieved in worms cultured in substrate media with a dose of 324 g m^{-2}	Yazid et al. (2021)

Table 2 Summary of studies on different culture media substrates used to rear *Eisenia fetida*

Culture media substrates	Observations	Reference
Aquaculture sludge (0%, 5%, 10%, 15%, 20%, 25%, and 50% dry weight basis)	Worm growth rates tended to increase with increasing sludge concentration, with the highest growth rate noted at 50% aquaculture sludge	Marsh et al. (2005)
Aquaculture sludge (40%, 50%, 60%, 70%, and 100%)	Maximum weight gain and chemical composition (phosphorus content) of the vermicompost were achieved in 100% and 40% broodstock aquaculture sludge, respectively	Gomah et al. (2020)
Aquaculture sludge	Increased weight and length were noted in earthworms cultured on aquaculture sludge after 21 days of vermicomposting	Belmeskine et al. (2023)
Citronella (*Cymbopogon winterianus* Jowitt) bagasse and paper mill sludge in the ratio of 3:2	There was increased earthworm biomass in animals cultured in citronella and paper mill sludge. Likewise, there was a decreased carbon–nitrogen ratio and humification index in vermicompost samples. However, increased concentration of copper, chromium, and iron was noted in vermicompost treatments	Boruah et al. (2019)
18 g vermiculite mixed with 2 g cow dung manure, pectin, cellulose, and humic acid	Growth rate and cocoon production slightly declined in the vermiculite growth media (7% organic matter) compared to the control media (cow dung, 70% organic matter)	Bouwman and Reinecke (1991)
Agrowastes (wheat straw and banana peels), bran (barley, rice, and gram bran), cow dung, and/or goat dung as tertiary combinations in the ratio of 1:1:1	The highest cocoon production was noted in the culture media composed of a mixture of cow dung, wheat straw, and rice bran, whereas the highest rate of reproduction (number of hatchings that emerged per cocoon) was noted in the culture media composed of cow dung, wheat straw, and barley bran. However, maximum biomass gain was noted in the culture media composed of goat dung, wheat straw, and gram bran	Chauhan and Singh (2013)
Waste biomass of potato and a mixture of potato waste biomass and cow dung in the proportion of 5:1	Mixing cow dung with potato waste biomass improved the quality of vermicompost final products as well as positively impacted the population of earthworms and biomass	Das and Deka (2021)

Table 2 (continued)

Culture media substrates	Observations	Reference
Rose, hypericum, and carnation flower wastes mixed with cow dung	Cocoon production started early, within approximately 2 weeks of clitellated worm introduction in culture media of rose flower wastes mixed with cow dung and hypericum flower wastes mixed with cow dung. The highest total number of cocoons was recorded in culture media composed of hypericum flower wastes mixed with cow dung, whereas the highest total number of hatchlings was recorded in culture media composed of rose flower wastes mixed with cow dung	Degefe and Tamire (2017)
Fermented residues of *Flammulina velutipes* and vinegar	The quantity and quality of earthworms cultured in the fermented *F. velutipes* and vinegar treatment groups significantly increased compared to those cultured in the cow dung group and the unfermented group	Xu et al. (2021)
Cattle manure pre-composted for 0, 1, 2, 3, 4, 5, and 6 weeks	No clear pattern was noted between the pre-composting times and the growth of earthworms. However, there was a decline in the number of cocoons with an increase in the pre-composting times. No clear pattern was noted in the pre-composting time and the number of earthworm hatchlings produced	Gunadi et al. (2002)
Duckweed (*Spirodela polyrhiza*) mixed with cow dung in 25%, 50%, 75%, and 100% ratios	High earthworm biomass (975–1395 mg) and fecundity (1.53–4.07 cocoons per worm) were noted in all the vermicompost treatments	Gusain and Suthar (2020)
Cow manure, goat manure, broiler chicken manure, market organic waste, household organic waste, rice straw, and beef rumen content	The highest number of earthworms and biomass was generated in the horse manure culture media treatment	Mashur et al. (2021)
Fermented paper mill wastewater sludge and cow dung in the ratios of 0%, 25%, 50%, 75%, and 100%	Fermentation of paper mill wastewater sludge mixed with cow dung increased both the microbial and earthworm populations	Negi and Suthar (2018)
Wheat straw and farmyard manure in the ratios of 1:1 and 1:1/2	*E. fetida* cultured in a 1:1 combination mixture exhibited better growth and reproduction	Panjgotra et al. (2016)
Animal fleshing was generated as solid waste from the leather industry, cow dung, and agricultural residues in the ratio of 3:1:1	Increased earthworm biomass was noted in the tested culture media. Moreover, the earthworms were able to convert the culture media into nutrient-enriched products	Ravindran et al. (2008)

Table 2 (continued)

Culture media substrates	Observations	Reference
Partly decomposed green gram waste with soil with percent substrate ratios (PSR): 10, 25, 50, 75, and 100	*E. fetida* kept in 100 PSR produced the maximum number of cocoons, which hatched out into a maximum number of young ones with a hatching rate of 0.9 hatching per cocoon. Hatching success was 91.7% after an incubation period of 29–32 days	Sathya and Deivanayaki (2015)
Herbal pharmaceutical industrial waste spiked in cow dung in ratios of 25%, 50%, 75%, and 100%	The high growth of *E. fetida* and the cocoon production rate were observed in all culture media substrate treatments	Singh and Suthar (2012)
Water lettuce (*Pistia* sp.) spiked with cow dung in the ratio of 20%, 40%, 60%, and 80%	*E. fetida* growth and reproduction rate were significantly high in the 60% and 80% treatment groups. Moreover, the same treatment groups exhibited maximum decomposition and mineralization rates	Suthar et al. (2017)
Biogas slurry, cow dung, wheat straw, leaf litter, sawdust, and kitchen waste	The biology and reproductive rates of *E. fetida* were 9 per month. Fertilized eggs of *E. fetida* developed into adults within 4 months	Tripathi and Bhardwaj (2004a)
Kitchen waste and cow dung	Rearing *E. fetida* in kitchen waste spiked with cow dung led to improved growth and reproduction after 150 days	Tripathi and Bhardwaj (2004b)
Partly decomposed sheep droppings with percent substrate ratios (PSR): 0, 25, 50, 75, and 100	Worms cultured in 75 PSR sheep droppings exhibited better growth and reproduction compared to other treatments	Deivanayaki and Nanthini (2016)

Table 3 Summary of studies on different culture media substrates used to rear *Enchytraeus albidus*

Culture media substrates	Observations	Reference
Plant-based diet or fish-based diet (commercial extruded seabass feed) in four different culture substrates: rice husk, peat, coco peat, and garden soil	The highest worm density (2220 worms/unit) was achieved in a plant-based diet combined with garden soil	Bahrioğlu et al. (2023)
Rolled oats ad libitum as feed with dried agricultural soil, dried and crushed seaweed (mainly *Fucus* spp.) as culture substrate	Maximum production of biomass can likely reach 80 g live worms/L/month at temperatures between 15 and 22 °C as indicated by improved growth performance in terms of specific growth rate, protein content, glycogen content, and fatty acid content	Dai et al. (2021)
Coffee grounds, spent brewing grains, stale bread, mixed produce, or sugar kelp	Improved growth performance was noted in white worms fed on coffee grounds, spent brewing grains, and stale bread. Likewise, worms fed on the aforementioned substrates contained mid-to-high protein and lipid contents	Fairchild et al. (2017)
Carbohydrates (wheat, bread, and milk); fruits (apple, banana, and date); vegetables (cabbage, spinach, potatoes, and carrot); trout pelleted feed; and a mixture of all these diets	Better growth performance was noted in worms fed on trout pelleted feed	Memi et al. (2004)
Agricultural soil and a mixture of rolled oats and dried seaweed (mainly *Fucus* spp.) at different salinities (0, 1, 2, 8, 15, 30, and 40 ppt)	Intermediate salinities (8–15 ppt) of the substrate led to maximum biomass production of white worms as well as increased protein and polyunsaturated fatty acids content	Holmstrup et al. (2020)

be taken when supplementing aquaculture feeds with feed alternatives to fulfill the dietary requirements of fish (Xing et al. 2024; Salamanca and Herrera 2025). Table 4 summarizes the concentration of essential amino acids (EAAs) in *Tubifex* sp., *E. fetida*, and *E. albidus*. These EAAs compositions are compared to the EAAs requirements of *O. niloticus* and those of *C. gariepinus*.

Influence of dietary supplementation of oligochaetes on fish and crustacean growth performance

Tubifex sp.

It is worth noting that successful hatchery production of fish fingerlings for stocking in grow-out production units largely depends on the availability of suitable live food organisms as feed for fish larvae, fry, and fingerlings (Lim et al. 2003). *Tubifex* sp. is one of the most commonly used worms as a natural feed in commercial larviculture and aquaculture production. Live worms are preferred as aquafeeds in larviculture and other young growth stages of fish because their mouth openings are small and their digestive systems are not yet fully developed to efficiently digest artificial feeds (Nuswantoro and Rahardjo. 2018). Furthermore, live feeds are highly palatable and have a high nutrient content (crude protein and fat) that is required for the proper growth and survival of aquaculture species (Malla and Banik 2015). Moreover, live feeds stimulate the secretion of digestive enzymes, resulting in good growth and survival (Khanom et al. 2022). Vasagam et al. (2007) noticed better final weight, weight gain, fry yield, and weight of newly released fry in *Poecilia latipinna* (Lesueur, 1821) fed on live tubifex compared to those fed on formulated feed. Feledi and Ronyai (2013) also observed that when Sterlet (*Acipenser ruthenus* L) larvae are fed on live tubifex worms from the beginning of feeding, their survival improved compared to those fed on artificial feed. A previous study by Sarkar et al. (2006) showed that feeding *Chitala chitala* (Hamilton) larvae on live tubifex worms enhanced their growth performance in terms of specific growth rate (SGR) and final mean weight. Apart from being administered as live feeds, tubifex can also be administered in different forms, such as dried tubifex, chopped, minced, or mixed with other feed ingredients. A reduction in growth performance was reported in *Pterophyllum scalare* (Kasiri et al. 2012) and *Trichogaster fasciata* (Nath et al. 2022) fed on dry tubifex worms. This could be attributed to the reduction in food quality under the drying process and this could explain why live feeds are preferred to dry tubifex feeds. However, mixtures of dry tubifex worms and other commercial diets or feed additives could enhance the quality and nutrient content of the aquafeed, leading to better growth performance. For instance, Syamsunarno and Sunarno (2022) observed that feeding post-larvae of *Channa striata* on a mixture of dry tubifex and commercial diet in the ratio of 50:50 improved the growth performance (feed conversion ratio (FCR), protein efficiency ratio (PER), SGR, and survival) of fish larvae. In another study, Rawat et al. (2018) also found that the incorporation of freeze-dried tubifex worms in a mixture of FM, fish oil (FO), and freeze-dried earthworm among other feed additives at the rate of 5% in the diets of *Ompok bimaculatus* (butter catfish) improved the growth and survival of fish fry.

Overall, the success of larviculture and aquaculture production depends on the availability of feeds rich in nutrients required for proper growth and survival. Table 5 summarizes studies on the influence of the dietary inclusion of tubifex worms in aquafeeds on the growth performance, immunity, flesh quality, and coloration of different aquaculture

Table 4 Essential amino acid composition (g/100 g crude protein) of oligochaetes and recommended requirements for *O. niloticus* and *C. gariepinus*

Amino acid	*Tubifex* sp.	*Eisenia fetida*	*Enchytraeus albidus*	*O. niloticus requirements*	*C. gariepinus requirements*
Phenylalanine	0.58–3.08	1.84–3.8	4.5	1.79	4.56
Histidine	0.36–2.64	1.36–2.5	2.25	1.72	1.0–1.05
Tryptophan	0.10–3.23	0.12–1.73	1.4	1.79	1.1–2.5
Arginine	0.71–2.94	2.48–4.41	6.0	4.2	1.97
Lysine	0.96–4.53	2.68–6.8	7.2	5.2	4.49–6.22
Leucine	0.89–4.37	3.12–16.6	7.9	3.39	4.87
Isoleucine	0.27–3.45	1.16–6.2	4.8	4.2	1.56
Methionine	0.35–3.63	0.76–1.2	2.6	3.21	1.87–2.97
Valine	0.39–2.62	1.32–4.7	5.4	2.8	2.08
Threonine	0.56–2.97	1.76–5.2	5.4	3.75	–2.04
References	Herawati et al. (2016)	Musyoka et al. (2019)	Holmstrup et al. (2022)	Santiago and Lovell (1988)	Langi et al. (2024)

Table 5 Growth performance, immune response, flesh quality, and coloration of different aquaculture species fed on different feed forms of *Tubifex* sp

Aquaculture species	Comment	Reference
Macrobachium rosenbergii	A combination of 25% *Tubifex* sp. worm feed and 75% cake feed for larvae prawn led to an improvement in SGR and FCR	Adhywirawan (2019)
Cyprinus carpio, *Carassius auratus auratus*, *Carassius auratus*	Fish fed with 50% commercial feed and 50% *Tubifex tubifex* in TF-2 showed significantly higher growth and survival performance	Alam et al. (2022)
Osphronemus goramy	Better growth performance in terms of SGR, FCR, condition factor, total length, body weight, and biomass gain at lower stocking densities were noted	Arifin et al. (2019)
Sander lucioperca	The highest SGR and condition factors were detected	Bódis et al. (2007)
Pangasianodon hypophthalmus	The feed mixture of chopped *Tubifex* sp. and other feed ingredients (egg yolk, mustard oil cake, nursery feed) exhibited the highest growth performance in terms of length, weight, and number	Chakraborty (2020)
Clarias batrachus	Non-bio-encapsulated *Tubifex* sp. significantly exhibited better final weight, SGR, and survival compared to bio-encapsulated *Tubifex* sp.	Dey et al. (2016)
Clarias macrocephalus	Highest growth rate, length increment, weight gain, and SGR 8 weeks after feeding	Evangelista et al. (2005)
Acipenser ruthenus L	Initial feeding of live-feed Siberian sterlets is preferable, as indicated by better growth performance (SGR, condition factor, final weight, and survival)	Feledi and Ronyai (2013)
Poecilia reticulata	Guppy reached marketable size (4–5 cm length) in 4 months (including larval stage) in mono sex culture with very high survival rates (98–99%) at a feeding rate of 3 days/week as supplementary frozen *Tubifex* sp. at a stocking density of 3 fish/L	Görelşahin et al. (2018)
Clarias macrocephalus	Supplementation of artificial feeds with live *Tubifex* sp. at 2% body weight improves growth and FCR of fry	Hashim et al. (1993)
Oreochromis niloticus	*Tubifex tubifex* cultured using 50 g/L of quail manure + 100 g/L of rice bran + 50 g/L of tofu, waste gave the best growth performance (survival rate, biomass, feed intake, PER) in fish	Herawati et al. (2020)
Pangasius bocourti	Survival rates and growth rates (final weight and SGR) were improved	Hung et al. (2002)
Pangasius bocourti (Sauvage 1880)	Improved survival rates and growth performance (SGR) for a 9-day nursing time	Hung et al. (1999)
Heteropneustes fossilis	Larvae fed with live feed exhibited better final body weight, body weight gain, average daily weight gain, final body length, and growth coefficient compared to dry feed	Khanom et al. (2022)
Ompok bimaculatus (Bloch, 1794)	Weight gain, SGR, and survival were highest in zooplankton plus *Tubifex* diet	Malla and Banik (2015)
Carassius auratus	Fry fed on custard and *Tubifex* significantly recorded higher survival rates, final weights, lengths, and SGR	Mathew et al. (2022)

Table 5 (continued)

Aquaculture species	Comment	Reference
Acipenser gueldenstaedtii	Larvae fed on both Artemia and *Tubifex* 12–16 and 17–18 d post-hatching exhibited good growth performance in terms of final weight and length	Memiş et al. (2009)
Poecilia reticulata (Peters, 1859)	Juvenile fish fed on *Tubifex* exhibited higher growth performance in terms of survival, condition factor, SGR, and final weight compared to the control diet	Mohideen and Altaff (2021)
Carassius auratus	Weight increment was high in groups fed with *Tubifex* and improved growth performance in terms of FCR and SGR	Mohanta and Subramanian (2002)
Clarias sp.	Chopping *Tubifex* worms into much smaller pieces facilitated easy feeding of the worms to catfish larvae, resulting in higher survival rates and SGR. However, no significant differences in growth performance were noted in larvae fed on chopped and unchopped feed	Nuswantoro and Rahardjo. (2018)
Macrobrachium lanchesteri	A feeding level of 5% body weight, three times a day, was found to be the most growth-promoting feeding regime	Panikkar et al. (2010)
Acipenser transmontanus	Fish larvae fed on live *Tubifex* exhibited better growth performance in terms of survival and growth	Randal and Doroshov (1984)
Acipenser ruthenus L	Survival rate improved when the larvae were fed on live feed from the beginning of feeding	Ronyai and Feledi (2012)
Catla catla	A combination of groundnut oil cake mixture and dried *Tubifex* improved the nutritive value and fatty acid contents of the muscle tissue of juveniles	Saravanan et al. (2015)
Chitala chitala (Hamilton)	Feeding fish larvae with live *Tubifex* worms post-hatching improved the SGR, final mean weight, weight gain, and survival	Sarkar et al. (2006)
Puntius filamentosus	Fry fed on live *Tubifex* had high final weight, length, weight, SGR, percentage weight gain, and percent length gain	Saurabh et al. (2013)
Notopterus chitala (Hamilton 1822)	Fry fed on live *Tubifex* exhibited no significant differences in survival, metabolic enzyme activity (ALT, AST), and digestive enzyme activity (cellulase and amylase) with other diets	Sontakke et al. (2019)
Oreochromis niloticus	Tilapia fingerlings fed on live *Tubifex* had better flesh quality	Pilot et al. (2014)
Channa striata	Feeding post larvae with dried *Tubifex* and commercial diet at the ratio of 50:50 exhibited better FCR, PER, SGR, and survival	Syamsunarno and Sunarno (2022)
Osteochilus vittatus	Larvae fed on live *Tubifex* worms from 20 to 40 days improved the growth performance in terms of final weight, absolute length, growth rate, SGR, and survival	Syandri et al. (2015)
Lates calcarifer	Poor survival, body protein, and lipid contents in fry fed on *Tubifex* worms were observed	Vartak and Singh (2009)
Carassius auratus	Feeding fish fry with bio-encapsulated *Lactobacillus* sp. in live *Tubifex* sp. improved the total weight gain and FCR of fish. Moreover, improvement in SGR and mean survival was noted	Abraham et al. (2010)

Table 5 (continued)

Aquaculture species	Comment	Reference
Clarias sp.	A combination of 75% commercial feed and 25% *Tubifex* sp. led to improved weight gain, absolute length, survival, and feed efficiency in fish	Agustina and Mukti (2021)
Clarias gariepinus Lin	Feeding fish fry with pond Tubifex sp. improved their growth performance in terms of length, weight, and survival	Ahmed et al. (1997)
Heteropneustes fossilis	Fish larvae fed on *Tubifex* sp. worms showed improvement in body length, weight gain, and specific growth rate	Ahmmed et al. (2016)
Osphronemus goramy	Fish juveniles fed on a combination of artificial feed and *Tubifex* sp. worm enhanced the digestive and growth performance of fish	Amriawati et al. (2021)
Pseudoplatystoma fasciatum	Juveniles fed on live Tubifex worms exhibited better survival and higher concentrations of fatty acids (20: 4n-6) in their tissues	Arslan et al. (2009)
Ompok pabda	Feeding fish larvae with a combination of zooplankton and *Tubifex* sp. led to improved survival, SGR, and increased body weight	Banik and Malla (2015)
Salmo trutta abanticus	A moderately improved growth performance (FCR, SGR, PER, daily growth rate index, weight gain, survival) was observed in fry-fed on *Tubifex* sp.	Bekcan and Atar (2012)
*Nandus nandus (*Hamilton 1822*)*	Moderate growth performance in terms of final weight, weight gain, and SGR was noted in N. nandus larvae fed on *Tubifex* sp.	Begum et al. (2017)
Xiphophorus helleri	Feeding *X. helleri* juveniles on *Tubifex* exhibited better survival, final weight, final length, weight gain, and SGR	Debnath et al. (2022)
Cherax destructor	Best survival and growth were observed in juvenile yabbies fed on *Tubifex* worms	Verhoef et al. (1998)
Heteropneustes fossilis Bloch	Best survival and growth were noted in fry-fed on *Tubifex* sp.	Haque and Barua (1989)
Anguilla anguilla	Elvers fed on *Tubifex* sp. exhibited better survival and the longest weaning period	El Hussieny et al. (2016)
Rita rita	Lower growth and survival were obtained in fish fed on live *Tubifex* sp.	Jalbani et al. (2019)
Pterophyllum scalare	Standard length, total length, percentage increase in total length, percentage increase in standard length, and percentage increase in weight were high in fish fed on *Tubifex*	Jayalekshmi et al. (2017)
Pterophyllum scalare	Moderate improvement in final weight, SGR, and FCR were noted in fish fed on dried *Tubifex* worms	Kasiri et al. (2012)
Colisa lalia	Improved coloration and survival were noted in fish fed on live *Tubifex* worms	Saha and Patra (2013)
Poecilia latipinna	*P. latipinna* fed on dry *Tubifex* meal performed better in terms of survival and SGR	Mohideen et al. (2014)

Table 5 (continued)

Aquaculture species	Comment	Reference
Trichogaster fasciata	Moderate growth performance was observed in larvae fed on a commercially available dried *Tubifex* meal	Nath et al. (2022)
Cyprinus carpio L	Improved coloration was noted in fish fed on a mixture of fish feed and *Tubifex* worms	Nica et al. (2020)
Cromobotia macracanthus	The *Tubifex* feed diet resulted in better weight gain, length gain, SGR, and FCR in fingerlings	Putra et al. (2019)
Clarias batrachus Lin	The best growth rate was achieved in fry-fed on Tubifex worms	Rahman et al. (1997)
Ompok bimaculatus	Improved growth performance in terms of final weight, weight gain, mean daily weight gain, and SGR were noted in fry-fed *Tubifex* worms	Rawat et al. (2018)
Chitala chitala	Feeding fish larvae on Tubifex led to improved SGR, percentage weight gain, and survival	Sarkar et al. (2007)
Poecilia latipinna	A mixture of oyster meat, live tubifex worms, and formulated feed led to improved growth performance (FCR, SGR, and weight gain) in brooders and juveniles	Vasagam et al. (2007)
Hucho taimen	Improved survival in larvae fed on a feed mixture of water fleas, *Tubifex,* and formulated feed or live food of water fleas and *Tubifex*	Wang et al. (2015)

SGR specific growth rate, *FCR* feed conversion ratio, *PER* protein efficiency ratio, *ALT* alanine transaminase, *AST* aspartate transaminase species. It is imperative to note that the replacement of commercial feed with cheaper, nutritious, and easily available feed alternatives is crucial in not only lowering the costs of production but also enhancing the growth performance and productivity of several aquaculture species (Mugwanya et al. 2022). Previous studies have shown that replacing a certain percentage of commercial feed with tubifex worms improves the growth performance and survival of different aquaculture species (Hashim et al. 1993; Agustina and Mukti 2021; Amriawati et al. 2021; Alam et al. 2022; Syamsunarno and Sunarno 2022). Agustina and Mukti (2021) investigated the potential of improving the productivity of catfish (*Clarias* sp.) seeds by feeding larvae on a mixture of 75% commercial feed and 25% *Tubifex* sp. and observed improved growth performance (weight gain, absolute length, feed efficiency, and survival) in fish larvae. Syamsunarno and Sunarno (2022) conducted a study on the dietary inclusion of dried tubifex worms in aquaculture diets (a combination of tubifex worms and artificial feed at a 50:50 ratio) of post-larval snakehead (*Channa striata*) and observed better growth performance in terms of PER, SGR, FCR, and survival. Amriawati et al. (2021) showed that feeding giant gourami (*Osphronemus goramy*) juveniles on a combination of artificial feed and tubifex worm in a biofloc system enhanced the digestive (protease activity, villi length, and surface area) and growth performance (average body weight, average body length, survival, and specific growth rate) of fish. Alam et al. (2022) also observed that the dietary inclusion of 50% tubifex worms in aquaculture diets improved the growth and survival of three ornamental fish species: *Cyprinus carpio*, *Carassius auratus auratus*, and *Carassius auratus*. Likewise, a combination of tubifex worms with other feed ingredients such as groundnut oil cake, mustard oil cake, egg yolk, oyster meat, and water fleas has been shown to improve the growth performance of several aquaculture species (Vasagam et al. 2007; Saravanan et al. 2015; Wang et al. 2015; Chakraborty 2020).

Quality parameters such as the coloration and freshness of fish flesh are important indices that determine the market value of fish (Amaya and Nickell 2015). With the increasing prices of FM and FO, the search for alternative feed ingredients has become a priority for sustainable aquaculture production (García-romero et al. 2014). Utilization of tubifex worms in aquafeeds has been shown to improve the coloration and flesh quality in *Cyprinus carpio* L. (Nica et al. 2020), *Colisa lalia* (Saha and Patra 2013), and *Oreochromis niloticus* (Pilot et al. 2014) respectively.

Eisenia fetida

Eisenia fetida belongs to the phylum Annelida, the family Lumbricidae, and to the subclass Oligochaeta, which is composed of more than 1300 species (Aguila Juárez et al. 2011). *E. fetida* (Savigny, 1826) is known under several common names such as manure worm, red earthworm, brandling worm, panfish worm, trout worm, tiger worm, and red wiggler worm, among others (Aguila Juárez et al. 2011; Sharma et al. 2019). It has been widely used in aquaculture diets to improve the growth performance and survival of several aquaculture species (Chiu et al. 2016; Mohanta et al. 2016; Kumlu et al. 2018; Musyoka et al. 2019, 2020a). Its successful utilization in aquafeeds is attributed to its high protein content that ranges from 50.1 to 70% (Bou-maroun et al. 2013; Gunya et al. 2016; Bhuvaneshwaran et al. 2019; Musyoka et al. 2020b; Gunya and Masika 2022; Kavle et al. 2023), fat content from 5 to 14% (Gunya and Masika 2022; Kavle et al. 2023), and ash content 3% (Kavle et al. 2023) depending on the culture conditions. These worms have a high reproduction rate and can tolerate a wide range of environmental conditions (Moroasui et al.

2022). Likewise, *E. fetida* is a surface dweller (epigeic) species; a trait that eases its mass production and harvesting (Musyoka et al. 2019).

E. fetida can be administered as a feed in different forms. The mixture of *E. fetida* with other feed ingredients is the most widely used form, followed by worm meal and live worms. Meeting the dietary protein requirements of any aquaculture species without compromising the palatability of the administered feed is vital to maximize production. Depending on the species, size, growth stage, and stocking density, among other factors, a protein content of 30–40% in aquaculture feeds is sufficient for the growth and well-being of several aquaculture species (Radhakrishnan et al. 2020), and hence, care should be taken during feed formulation. Zakaria et al. (2012) investigated the optimization of protein content in earthworm-based feed formulation for *C. gariepinus* and observed that a mixture of 25% earthworm powder, 25% soybean waste, and 5.95% chicken guts yielded an optimum protein content of 35.97% that was suitable for the growth and general wellbeing of the fish. In another study, Djissou et al. (2016) reported that a mixture of earthworm meal and maggots in the ratio of 2:5 yielded a protein content of 40% suitable for improved growth performance (FCR, PER, SGR, and survival) of *C. gariepinus*. Chiu et al. (2016) also observed that fermentation of a mixture of soybean meal and earthworm meal (4:1 ratio) with *Bacillus subtilis* E-20 yielded a crude protein content of 37%, which was suitable for the proper growth of *Penaeus vannamei*. It is imperative to note that the successful utilization of *E. fetida* in aquaculture diets depends on several factors, such as handling and feed processing techniques (Vital et al. 2016; Musyoka et al. 2020a). Generally, earthworms release a foul-smelling coelom fluid that comprises lysine and hemolytic factors that cause toxicity and unpalatability to fish (Kobayashi et al. 2001; Musyoka et al. 2020a). Their exoskeleton is composed of chitin, an antinutritional molecule that, if not broken down during feed formulation, would suppress the growth of aquaculture species (Musyoka et al. 2020a). Therefore, the removal of the gut contents of *E. fetida*, boiling, drying, and milling is vital to improve the nutrient availability and acceptability of the final product. Table 6 summarizes the results on the growth performance of different aquaculture species fed on different forms of *E. fetida*.

Enchytraeus albidus

The white worm (*Enchytraeus albidus*) belongs to the phylum Annelida, the family Lumbriculidae, and the class Oligochaeta (Kolesnyk et al. 2019; Tamilarasu et al. 2020). There are about 40 species of white worms that come under different genera (Tamilarasu et al. 2020). *E. albidus* are quite similar to the earthworm, but they are white in color and highly rich in protein (Tamilarasu et al. 2020). Their protein content ranges from 42.8 to 70% (Memi et al. 2004; Fairchild et al. 2017; Holmstrup et al. 2020), fat content from 10 to 27% (Memi et al. 2004; Fairchild et al. 2017; Holmstrup et al. 2020), and ash content from 2.3 to 8% (Memi et al. 2004; Fairchild et al. 2017; Holmstrup et al. 2020). They are considered a potential feed for both marine and freshwater aquaculture species (Fairchild et al. 2017; Kolesnyk et al. 2019; Tamilarasu et al. 2020), though they may need enrichment in n-3 long-chain polyunsaturated fatty acids (Ruby et al. 2024). Despite their economic importance in both larviculture and aquaculture, there is very limited literature on the dietary inclusion of *E. albidus* in aquaculture diets. Furthermore, the most commonly reported feed form where the live feed compared to other forms, such as mixture and frozen feed form. *E. albidus* serves as an excellent alternative feed in commercial larviculture, especially during the late larval development stage, where the larvae need to feed on larger-sized live feeds

Table 6 Growth performance and immune response of different aquaculture species fed on different feed forms of *Eisenia fetida*

Aquaculture species	Comment	Author
Rutilus caspicus	Improved weight gain, SGR, and FCR (diluted extract of 1:25 v/v gave the best results)	Rufchaei et al. (2019)
Cyprinus carpio L	Increased microbial diversity and abundance in the intestine, 15.1% earthworm meal, and 1.8% worm cast had no adverse effect on growth performance and enhanced antioxidant and immune capacity	Mi et al. (2022)
Oreochromis niloticus	Replacement of FM by 30% mixture improved the weight gain and biomass of fish. 100% FM replacement had the highest economic returns and profit index due to the low cost of producing the earthworm bedding	Musyoka et al. (2020a)
Penaeus vannamei (Boone)	*Bacillus subtilis* E20 fermentation improved the mixture's palatability (soybean meal and *Eisenia fetida* in the ratio of 4:1) and utilization based on better growth performance. Maximal replacement levels of FM with FSFEM were 80% in a shrimp diet with 37% of crude protein and 7% of crude lipid based on weight gain and 100% based on feeding efficiency	Chiu et al. (2016)
Cyprinus carpio L	A mixture of earthworm and duckweed had the highest acid phosphatase (ACP) and alkaline phosphatase (AKP) activity in the liver and increased enzyme immune responses	Zhao et al. (2020)
Cyprinus carpio L	A mixture of earthworm and duckweed increased the microbial diversity and abundance of the intestine, higher activity of immune enzymes such as acid phosphatase, phosphatase (AKP), lysozyme, total antioxidant capacity, superoxide dismutase, catalase, glutathione peroxidase. In addition, a lower level of metabolites was also detected, such as nitric oxide and malondialdehyde	Yang et al. (2019)
Labeo rohita	Pelleted earthworms significantly improved FCR, SGR, protein retention efficiency, and energy retention efficiency	Mohanta et al. (2016)
Trichogaster trichopterus	Fish fed on earthworm meal exhibited increased growth performance in terms of weight gain, FCR, SGR, and PER	Mohanta et al. (2013)
Mystus montanus	Increased PER, SGR, Weight gain, and improved FCR	Sakthika et al. (2014)
Xiphophorus hellerii	10% earthworm meal showed the highest growth performance regarding mean body weight	Boaru et al. (2016)
Astronauts ocellatus	Improved growth performance in terms of weight increase, length increase, growth rate%, SGR, and condition factor	Seidgar et al. (2022)
Oncorhynchus mykiss	Unpalatable to fish	Tacon et al. (1983)
Oreochromis niloticus L. *and Cyprinus carpio* L. post larvae	Increased growth and weight gain in post-larvae, and higher lipid content in the larvae	De Chaves et al. (2015)
Heteropneustes fossilis	Improved body weight and length, average daily weight gain, SGR, FCR	Kumar et al. (2022)

Table 6 (continued)

Aquaculture species	Comment	Author
Catla catla, Labeo rohita, Cirrhinus mrigala	50% replacement of FM gave the best results for growth and fish yield	Beg et al. (2016)
Clarias gariepinus	Weight gain, FCR, SGR, and survival percentage were not as good as those of fish fed on tilapia	Moroasui et al. (2022)
Parachanna obscura	50% FM replacement exhibited a better growth rate and FCR. 25% and 50% Fishmeal replacement gave similar results in terms of feed efficiency, protein efficiency rate, and SGR	Vital et al. (2016)
Clarias gariepinus fingerlings	This study indicates that when the ratio of 2:5 between the earthworm meal and the maggot meal is used to entirely replace fish meal, and the ratio of lysine/arginine of the diet is inferior to 1, the growth performances and feed utilization of *Clarias gariepinus* fingerlings are improved	Djissou et al. (2016)
Cyprinus carpio L. fingerlings	Improved feeding efficiency, protein utilization efficiency, food conversion ratio, and average daily gain	Coroian et al. (2015)
Clarias gariepinus	Enhanced growth performance in terms of SGR, WG, AFW, and survival	Houndonougbo et al. (2021)
Oreochromis niloticus	The incorporation of 13.82% earthworm powder in aquaculture diets improved the SGR and survival of fish	Houndonougbo et al. (2017)
Oreochromis niloticus	Dietary inclusion of 75% earthworm meal in aquaculture diets improved the SGR, WG, AFW, and survival of fingerlings	Ahmed et al. (2020)
Oreochromis niloticus	Feeding *O. niloticus* fingerlings on a diet containing a mixture of *Azolla filiculoides* and *Eisenia fetida* in the ratios of 2:1 and 1:5 improved their SGR and FCR	Arnauld et al. (2017)
Oncorhynchus mykiss	Dietary inclusion of 30% earthworm meal in aquaculture diets enhanced the growth performance in terms of WG, FCR, PER, and SGR	Karabulut et al. (2020)
Clarias gariepinus	Replacement of *Caridina nilotica* with 50% *E. fetida* and 25% *Spirulina platensis* improved the survival of fish under ammonia stress conditions	Onura et al. (2022)
Clarias gariepinus	Replacement of *Caridina nilotica* with 50% *E. fetida* enhanced the growth performance of fish in terms of growth, nutrient utilization, and survival	Onura et al. (2022)
Oncorhynchus mykiss	No significant differences in FW were noted in fish fed on whole frozen earthworms in different levels (25%, 50%, and 75%)	Pereira and Gomes (1995)
Oreochromis niloticus	Replacement of fishmeal with 5, 10, and 15% earthworm meal did not compromise the growth performance and hematological parameters of fish	Russio et al. (2022)
Poecilia reticulata	Fish fed on earthworm meal exhibited increased brood number and produced twice the offspring compared to those fed on standard feed	Kostecka and Pączka (2006)

Table 6 (continued)

Aquaculture species	Comment	Author
Clarias gariepinus	Results showed that the replacement of fishmeal with earthworm meal, not exceeding 50%, improved the growth performance of fish	Tadesse et al. (2021)
Clarias gariepinus	A combination of earthworm powder, soybean waste, and chicken guts at the rate of 25%, 25% and 5.95%, respectively, provided the necessary protein requirements needed for the growth of fish	Zakaria et al. (2012)

FM fish meal, *FSFEM Bacillus subtilis* E20-fermented mixture, *SGR* specific growth rate, *FCR* feed conversion ratio, *PER* protein efficiency ratio, *WG* weight gain, *AFW* average final weight to obtain the necessary nutrients required for growth (Holmstrup et al. 2022). Utilization of *E. albidus* as an aquafeed has been documented in several aquaculture species to improve their growth performance, as shown in Table 7.

Economic feasibility of oligochaete worm production

As sustainable aquaculture and agriculture gain momentum, the economic prospects of oligochaete production are likely to continue improving. For instance, *E. fetida* production, commonly known as vermicomposting, not only generates worm biomass that can be used as an animal protein but also generates a valuable organic fertilizer whose application has been shown to improve the soil physiochemical properties and crop yields (Helena et al. 2015; Gebrehana 2018; Getachew et al. 2023). Moreover, vermicomposting has been reported as one of the sustainable ways to reduce organic waste in the environment (Alshehrei and Ameen 2021; Kauser and Khwairakpam 2022). As such, for small-scale and medium-sized farms with access to large quantities of organic wastes, integrating vermicomposting to generate earthworm meal for on-farm feed formulations is one of the most cost-effective ways to reduce aquaculture and agriculture production costs. For instance, Belewu et al. (2023) showed that replacement of 50% FM with earthworm meal in the diets of the African catfish (*C. gariepinus*) results in a higher profitability index of 2.74, rate of return on capital of 1.02, and marketing margin of 6.30 compared to the control (100% FM). In another study, Garcia et al. (2025) showed a 5.8% reduction in feed costs with hydrolysed earthworm meal in *O. niloticus*. Musyoka et al. (2020a) reported improved economic returns and profit index in *O. niloticus* fingerlings fed on 100% earthworm bedding meal compared to the control diets due to the low costs of producing earthworm bedding. For *Tubifex* sp. and *E. albidus* our literature search did not yet any results on the profitability index and economic returns of these species hence more studies are needed to elucidate the economic feasibility of their mass production.

Potential risks and production challenges

One of the major challenges in live feed production, especially for oligochaetes, is the quality of the substrate used to culture these worms. Manure of animal or poultry origin has been used as part of the substrate in combination with other materials to grow these worms (Munnoli and Bhosle 2009; Ngosong et al. 2020; Ferraz Ramos et al. 2022; Chaudhari and Barot 2024). However, the existence of residual antibiotics in manure poses a serious threat to the emergence of antibiotic resistance genes (ARGS) in larviculture and aquaculture production systems (Muziasari et al. 2017; Zhou et al. 2020; Wang et al. 2024). Moreover, increased concentrations of commonly used human and veterinary antibiotics, such as sulfonamides, tetracyclines, and fluoroquinolones, lower the abundance of worms as well as alter their gut microbiome (Narciso et al. 2023). A previous study by Zhao et al. (2022) showed that exposing earthworms to a multi-antibiotic contaminated agricultural soil derived from a long-term manure exposure resulted in a significant decrease in the biomass of earthworms, especially for oxytetracycline and famethazine. In another study, Parente et al. (2021) observed that earthworms (*E. andrei*) exposed to high concentrations of enrofloxacin and ciprofloxacin present in poultry manure for 48 h not only exhibited an "avoidance behavior" but also died 7 to 14 days post-exposure. Dairy and sewage sludge

Table 7 Growth performance of different aquaculture species fed on *Enchytraeus albidus*

Aquaculture species	Comment	Reference
Salmo trutta	The addition of white worms in fish diets (0.25% and 0.5%) slightly improved the weight gain of fish. There was an improvement in feed conversion ratio in fry fed with live white worms, followed by those fed on 0.5% and 0.25% white worms	Yanık et al. (2017)
Pseudopleuronectes americanus	Improved survival, standard length, and mean stomach content index were noted in fish fed on live feed (*E. albidus*)	Walsh et al. (2015b)
Pseudopleuronectes americanus	Fish fed on live feed (*E. albidus*) exhibited better survival and growth	Walsh et al. (2015a)
Herotilapia multispinosa and *Amatitlania nigrofasciata*	Improved growth performance and survival in fish (*A. nigrofasciata*) fed on live feeds were noted	Tosun and Simsar (2018)
Xiphophorus maculatus Günther, 1866	Fish fed on frozen white worms or a mixture of frozen white worms and aquarium fish feed exhibited better growth performance regarding weight gain	Şahİn et al. (2017)
Platichthys flesus	Juvenile flounder fed on white worms grew twice as fast as fish fed on a commercial dry feed	Holmstrup et al. (2022)

are among the most commonly used substrates in the biomass production of *Tubifex* sp. and *E. fetida*. However, these substrates could introduce potentially pathogenic microorganisms that can lead to a decline in biomass production (Jezierska-tys et al. 2010; Frac et al. 2017). Additionally, a variety of toxic heavy metals can be found in sewage sludge (Geng et al. 2020; Alengebawy et al. 2021), whose intake and accumulation in cultured worms could pose a serious health risk to fish (Garai et al. 2021; Shahjahan et al. 2022).

The use of agricultural waste biomass, such as rice straw, wheat straw, and or/leaf litter, could introduce pesticide residues in the culture media that can harm the worms (Pelosi et al. 2021; Nkontcheu et al. 2023). Even though these worms survive, the risk of their bioaccumulation in the food chain is high, which could pose a danger to fish and consumers. Additionally, the use of plant-based feed in Oligochaeta nutrition could result in reduced feed intake and growth. This is because plants contain anti-nutritional inhibitors that could interfere with nutrient assimilation in oligochaetes. Likewise, plants lack certain essential amino acids, hence not the best source of protein for cultured oligochaetes (Musyoka et al. 2019). Another potential risk would be the transmission of blood parasites (Zazouli et al. 2021) and prions, especially in culture media consisting of cattle blood as a wetting agent. Nematodes have been reported to ingest and excrete infectious prions, which could pose a danger to other organisms (Pritzkow et al. 2021).

Besides the above-mentioned potential risks, improper infrastructure could hinder the large-scale production of oligochaetes. In their review, Enebe and Erasmus (2023) discussed the limitations of several vermicompost production systems and concluded that certain vermicompost technologies, such as the batch scale, could still incur higher costs of labor and anaerobiosis development in the reactor, which could hinder fecundity and survival. Aquatic oligochaetes such as Tubifex require a continuous water flow under optimum oxygen and temperature (22–27 °C) conditions (Jewel et al. 2016). Such conditions could be challenging to maintain, especially in arid and semi-arid regions due to extremely high temperatures and water scarcity. Moreover, the energy costs to run pumps and aerators could increase the cost of production. Furthermore, using other water sources, such as municipal wastewater, requires chlorination to disinfect the water before downstream use, which might introduce chlorination byproducts (e.g., trihalomethanes and haloacetic acids) that are toxic to aquatic life forms (Parveen et al. 2024; Li et al. 2025).

Management strategies and future research perspectives

Effective management strategies involve periodic monitoring of the environmental conditions and health status of worms. For aquatic oligochaetes, monitoring of water quality parameters such as ammonia, temperature, dissolved oxygen, and pH is essential for growth maintenance. Water filtration to remove suspended solids and aeration to maintain optimum concentrations of dissolved oxygen will reduce the pathogen transmission and outbreak of diseases. It is imperative to note that the sterilization of oligochaetes, such as Tubifex and white worms, before being fed to fish larvae is paramount in the prevention of contamination and disease outbreaks. As such, farmers should be taught proper sterilization techniques, feeding strategies, and disease identification to optimize production. Additionally, farmers should be sensitized against using certain wetting agents, such as cattle blood in the culture media of oligochaetes, as this would increase the risk of parasite and pathogen transmission. Utilization of fish pellets as a feed for oligochaetes reduces the risk of pathogen and parasite transmissions while promoting a well-balanced nutrient profile in worms.

As mentioned above, culture substrates have a profound influence on the nutrient profile of oligochaetes. For example, white worms are deficient in highly unsaturated fatty acids (HUFAs); thus, more studies are needed to improve the fatty acid content in white worms. Microalgae are rich sources of fatty acids, especially the highly unsaturated fatty acids (HUFAs) (Remize et al. 2021; Rojas et al. 2023). Hence, their inclusion in the diets of white worms will improve their fatty acid content, which, when fed to fish larvae, will fulfil their dietary fatty acid requirements. More studies are needed to understand the impact of the fermentation of plant-based feed sources and microalgae on the growth performance and nutrient profile of oligochaetes.

Conclusions

The utilization of oligochaetes as feeds in larviculture and aquaculture nutrition offers profound benefits, including improved growth performance, survival, and cost efficiency. In spite of the fact that there are certain production challenges and associated risks, with proper management and feeding strategies, oligochaetes can become a feasible, sustainable, cost-effective solution for aquaculture farmers. However, more studies on the economic feasibility of *Tubifex* sp. and *E. albidus* production are needed.

Acknowledgements The authors would like to thank Mr. Fahad Kimera, CARES manager for agriculture, for his support during the drafting of this manuscript.

Author contribution Conceptualization: M. A.O. D. and M.M. conceptualized the manuscript. M.M. wrote the original draft. Supervision: M. A.O. D. and H.S. contributed the Resources. All authors reviewed the manuscript.

Funding Open Access funding enabled and organized by Projekt DEAL.

Data availability No datasets were generated or analysed during the current study.

Declarations

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

References

Abraham TJ, Dasgupta A, Banerjee T (2010) Effect of feeding bioencapsulated *Lactobacillus* sp. in live *Tubifex* sp. on the growth performance of gold fish *Carassius auratus* (Linnaeus,1758). Bangladesh J Fish Res 14:1–8

Adhywirawan G (2019) Effectiveness of feed combination from cake and tubifex on feed conversion ratio, specific growth rate and survival rate of *Macrobrachium rosenbergii*. IJOTA 1(1):23–3. https://doi.org/10.22219/ijota.v1i1.5938

Aguila Juárez PD, Lugo de la Fuente J, Vaca Paulín R (2011) Vermicomposting as a process to stabilize organic waste and sewage sludge as an application for soil. Trop Subtrop Agroecosystems 14:949–963

Agustina D, Mukti RC (2021) The influence of feeding combination silkworm (*Tubifex* sp.) with commercial feed on growth performance of catfish (*Clarias* sp.). Acta Aquat Aquat Sci J 2:74–77

Ahmed GU, Islam MF, Khan MNA et al (1997) Culture feasibility of African catfish (*Clarias gariepinus* Lin.) fry in glass tank and synthetic hapa system using supplemental diets. Bangladesh J Fish 1:59–66

Ahmed RA, Eissa HS, Shafi ME et al (2020) Influence of replacement of fish meal with the earthworm *Eisenia fetida* on growth performance, feed utilization and blood parameters of Nile tilapia (*Oreochromis niloticus*). J Aquac Mar Biol 9:37–42. https://doi.org/10.13140/RG.2.2.23785.31845

Ahmmed MK, Ghosh SK, Sarkar J et al (2016) Impacts of different diets on growth and survival of stinging catfish, *Heteropneustes fossilis*. Bangladesh J Vet Anim Sci 4:22–26. https://doi.org/10.13140/RG.2.2.29452.56968

Alam A, Khan AM, Mahfuj S et al (2022) A model for tubificid worm (*Tubifex tubifex*) production and its effect on growth of three selected ornamental fish. Bangladesh J Fish 33:205–214. https://doi.org/10.52168/bjf.2021.33.23

Alengebawy A, Abdelkhalek ST, Qureshi SR, Wang M (2021) Heavy metals and pesticides toxicity in agricultural soil and plants: ecological risks and human health implications. Toxics 9:42

Alshehrei F, Ameen F (2021) Vermicomposting: a management tool to mitigate solid waste. Saudi J Biol Sci 28:3284–3293. https://doi.org/10.1016/j.sjbs.2021.02.072

Amaya E, Nickell D (2015) Using feed to enhance the color quality of fish and crustaceans. Feed and feeding practices in aquaculture. Woodhead Publishing Series in Food Science, Technology and Nutrition, pp 269–298

Amriawati E, Budiardi T, Setiawati M et al (2021) Digestive system and growth performance of giant gourami (*Osphronemus goramy* Lacepede) juveniles in biofloc systems fed with different feed types. Aquac Res 52:4661–4669. https://doi.org/10.1111/are.15300

Ansari FA, Guldhe A, Gupta SK et al (2021) Improving the feasibility of aquaculture feed by using microalgae. Environ Sci Pollut Res 28:43234–43257. https://doi.org/10.1007/s11356-021-14989-x

Arifin OZ, Prakoso VA, Subagja J et al (2019) Effects of stocking density on survival, food intake and growth of giant gourami (*Osphronemus goramy*) larvae reared in a recirculating aquaculture system. Aquaculture 509:159–166. https://doi.org/10.1016/j.aquaculture.2019.05.010

Arnauld SM, Djissou M, Ochiai A et al (2017) Effect of total replacement of fishmeal by earthworm and *Azolla filiculoides* meals in the diets of Nile tilapia *Oreochromis niloticus* (Linnaeus, 1758) reared in concrete tanks. Indian J Fish 64:31–36. https://doi.org/10.21077/ijf.2017.64.1.55317-05

Arslan BM, Dabrowski K, Portella MC (2009) Growth, fat content and fatty acid profile of South American catfish, surubim (*Pseudoplatystoma fasciatum*) juveniles fed live, commercial and formulated diets. J Appl Ichthyol 25:73–78. https://doi.org/10.1111/j.1439-0426.2008.01154.x

Bahrioğlu E, Isa HM, Cengiz S, Erean E (2023) The effect of fish meal and plant-based diets on the growth and nutritional composition of white worms (*Enchytraeus albidus* Henle, 1837) in various substrates. Pak J Zool 55:563–570. https://doi.org/10.17582/journal.pjz/20211028111008

Banik S, Malla S (2015) Survival and growth rate of larval *Ompok pabda* (Hamilton-Buchanan, 1822) of Tripura, India: related to efficient feed. Proc Zool Soc 68:164–171. https://doi.org/10.1007/s12595-014-0111-x

Beg MM, Mandal B, Moulick S (2016) Potential of earthworm meal as a replacement of fish meal for Indian major carps. Int J Fish Aquat Stud 4:357–361

Begum M, Noor P, Ahmed KN et al (2014) Development of a culture techniques for Tubificid worm, under laboratory conditions. Bangladesh J Zool 42:117–122

Begum N, Pramanik MH, Mahmud Y (2017) Growth and survival rate of *Nandus nandus* (Hamilton 1822) larvae on some selected supplemental feeds in cistern. Asian J Med Biol Res 3(1):114–119. https://doi.org/10.3329/ajmbr.v3i1.32046

Bekcan S, Atar HH (2012) Effects of live feeds and compounded diet on growth parameters of brown trout fry (*Salmo trutta* abanticus T. 1954) in the context of habitat restoration. J Agric Sci 137–145. https://doi.org/10.1501/Tarimbil

Belewu MA, Sadiq HO, Belewu KY et al (2023) Dietary evaluation and partial budget analysis of earthworm meal based diet on the performance characteristics of catfish (*Clarias gariepinus*). ASRIC J Nat Sci 3:83–90

Belmeskine H, Dilmi N, Tsagadirts Z (2023) Aquacultural sludge recovery and vermicomposting for soil amendment : a useful strategy for sustainable agriculture. Int J Recycl Org Waste Agric 12:111–121. https://doi.org/10.30486/IJROWA.2022.1944998.1372

Bhuvaneshwaran T, Sanjay G, Jayakumar N et al (2019) Potentiality of earthworm as a replacement for fishmeal and its role in aquaculture. J Aquac Tropics 34:115–127. https://doi.org/10.32381/JAT.2019.34.1-2.10

Boaru A, Struţi D, Dărăban SV, Georgescu B (2016) The effect of using earthworm meal (*Eisenia foetida*) as protein supplement for the growth of *Xiphophorus hellerii* juveniles. Poeciliid Res 6:4–9

Bódis M, Kucska B, Bercsé M (2007) The effect of different diets on the growth and mortality of juvenile pikeperch (*Sander lucioperca*) in the transition from live food to formulated feed. Aquacult Int 15:83–90. https://doi.org/10.1007/s10499-006-9063-0

Boruah T, Barman A, Kalita P et al (2019) Vermicomposting of citronella bagasse and paper mill sludge mixture employing *Eisenia fetida*. Bioresour Technol 294:122147. https://doi.org/10.1016/j.biortech.2019.122147

Bou-maroun E, Loupiac C, Loison A et al (2013) Impact of preparation process on the protein structure and on the volatile compounds in *Eisenia foetida* protein powders. Food Nutr Sci 4:1175–1183. https://doi.org/10.4236/fns.2013.411151

Bouwman H, Reinecke AJ (1991) A defined medium for the study of growth and reproduction of the earthworm *Eisenia fetida* (Oligochaeta). Biol Fertil Soils 10:285–289

Cahu C, Infante JZ (2001) Substitution of live food by formulated diets in marine fish larvae. Aquaculture 200:161–180. https://doi.org/10.1016/S0044-8486(01)00699-8

Chakraborty BK (2020) Rearing and nursing of Thai pangas, *Pangasianodon hypophthalmus* (Sauvage, 1978) with different feeds. International Journal of Biological Innovations 02:277–284. https://doi.org/10.46505/ijbi.2020.2224

Chaudhari F, Barot J (2024) Poultry manure vermicompost by *Eisenia foetida* and its impact on vegetable crops. African J Biol Sci 6:4375–4387. https://doi.org/10.48047/AFJBS.6.15.2024.4375-4388

Chauhan HK, Singh K (2013) Effect of tertiary combinations of animal dung with agrowastes on the growth and development of earthworm *Eisenia fetida* during organic waste management. Int J Recycl Org Waste Agric 2:1–7

Chaves R, Paula R, Gücker B et al (2015) An alternative fish feed based on earthworm and fruit meals for tilapia and carp postlarvae. Braz J Biosci 15:15

Chiu ST, Wong SL, Shiu YL et al (2016) Using a fermented mixture of soybean meal and earthworm meal to replace fish meal in the diet of white shrimp, *Penaeus vannamei* (Boone). Aquac Res 47:3489–3500. https://doi.org/10.1111/are.12799

Coroian CO, Mireşan V, Cocan DI et al (2015) Growth performance of common carp (*Cyprinus carpio* L.) fingerlings fed with various protein levels. AACL Bioflux 8:1038–1047

Dai W, Slotsbo S, Holmstrup M (2021) Thermal optimum for mass production of the live feed organism *Enchytraeus albidus*. J Therm Biol 97:102865. https://doi.org/10.1016/j.jtherbio.2021.102865

Das D, Deka H (2021) Vermicomposting of harvested waste biomass of potato crop employing *Eisenia fetida*: changes in nutrient profile and assessment of the maturity of the end products. Environ Sci Pollut Res 28:35717–35727

Debnath S, Sarker DS, Kundu P (2022) Growth, survival and body protein content of Swordtail (*Xiphophorus helleri*) fed live and formulated feeds. Adv Anim Vet Sci 10:335–341. https://doi.org/10.17582/journal.aavs/2022/10.2.335.341

Degefe G, Tamire G (2017) Growth and reproductive performance of *Eisenia fetida* in three varieties of flower (rose, carnation and hypericum) leftovers. J Entomol Nematol 9:29–35. https://doi.org/10.5897/JEN2017.0181

Deivanayaki M, Nanthini R (2016) Effect of different sheep droppings media on the growth and cocoon production of *Eisenia fetida*. Res J Sci Technol 8:142. https://doi.org/10.5958/2349-2988.2016.00020.6

Derby CD, Elsayed FH, Williams SA et al (2016) Krill meal enhances performance of feed pellets through concentration-dependent prolongation of consumption by Pacific white shrimp, *Litopenaeus vannamei*. Aquaculture 458:13–20. https://doi.org/10.1016/j.aquaculture.2016.02.028

Devic E, Leschen W, Murray F, Little DC (2018) Growth performance, feed utilization and body composition of advanced nursing Nile tilapia (*Oreochromis niloticus*) fed diets containing Black Soldier Fly (*Hermetia illucens*) larvae meal. Aquacult Nutr 24(1):416–423. https://doi.org/10.1111/anu.12573

Dey A, Ghosh K, Hazra N (2016) Evaluation of preference of dry feed, bio-encapsulated and non bio-encapsulated live feed and survival of the walking catfish *Clarias batrachus* (L.) juveniles. Int J Fish Aquat Stud 4:545–549

Djissou ASM, Adjahouinou DC, Koshio S, Fiogbe ED (2016) Complete replacement of fish meal by other animal protein sources on growth performance of *Clarias gariepinus* fingerlings. Int Aquat Res 8:333–341. https://doi.org/10.1007/s40071-016-0146-x

El Hussieny OM, Abd-El Samee AM, Ghonimy AMA et al (2016) The effect of different pre-weaning diets and feeding methods on survival rate of elvers, Anguilla anguilla. Egypt J Nutr Feed 19:139–146. https://ejnf.journals.ekb.eg/article_74881_4d75de9e6cbc7ffac128aecf6bb5ac81.pdf

Enebe MC, Erasmus M (2023) Vermicomposting technology-a perspective on vermicompost production technologies, limitations and prospects. J Environ Manage 345:118585. https://doi.org/10.1016/j.jenvman.2023.118585

Evangelista AD, Fortes NR, Santiago CB (2005) Comparison of some live organisms and artificial diet as feed for Asian catfish *Clarias macrocephalus* (Günther) larvae. J Appl Ichthyol 21:437–443. https://doi.org/10.1111/j.1439-0426.2005.00643.x

Fairchild EA, Bergman AM, Trushenski JT (2017) Production and nutritional composition of white worms *Enchytraeus albidus* fed different low-cost feeds. Aquaculture 481:16–24. https://doi.org/10.1016/j.aquaculture.2017.08.019

Feledi T, Ronyai A (2013) Preliminary results on Siberian sterlet fry rearing and their comparison with some production performance parameters of “European” sterlet. Turk J Fish Aquat Sci 13:447–452. https://doi.org/10.4194/1303-2712-v13

Ferraz Ramos R, Almeida Santana N, de Andrade N et al (2022) Vermicomposting of cow manure: effect of time on earthworm biomass and chemical, physical, and biological properties of vermicompost. Bioresour Technol 345. https://doi.org/10.1016/j.biortech.2021.126572

Frac M, Jezierka-Tys S, Oszust K et al (2017) Assessment of microbiological and biochemical properties of dairy sewage sludge. Int J Environ Sci Technol 14:679–688. https://doi.org/10.1007/s13762-016-1179-9

Garai P, Banerjee P, Mondal P, Saha NC (2021) Effect of heavy metals on fishes : toxicity and bioaccumulation. J Clin Toxicol S:001

Garcia FGM, Quila NV, Franco LFL et al (2025) Effect of hydrolyzed red worm (*Eisenia foétida*) on production parameters in red tilapia (*Oreochromis* sp.). F1000Res 14:1–21

García-romero J, Ginés R, Izquierdo MS et al (2014) Effect of dietary substitution of fish meal for marine crab and echinoderm meals on growth performance, ammonia excretion, skin colour, and flesh quality and oxidation of red porgy (P*agrus pagrus)*. Aquaculture. https://doi.org/10.1016/j.aquaculture.2013.11.024

Gebrehana ZG (2018) Vermicompost potential of common earthworms (*Eudrilus eugeniae*) and red wiggler (*Eisenia fetida*) worm on the decomposition of various organic wastes. Int J Plant Soil Sci 24:1–13. https://doi.org/10.9734/IJPSS/2018/42986

Geng H, Xu Y, Zheng L et al (2020) An overview of removing heavy metals from sewage sludge : achievements and perspectives. Environ Pollut 266:115375. https://doi.org/10.1016/j.envpol.2020.115375

Getachew Z, Gebremikael MT, Beyene S et al (2023) Organic residue valorization for Ethiopian agriculture through vermicomposting with native (*Eudrilus eugeniae*) and exotic (*Eisenia fetida* and *Eisenia andrei*) earthworms. Eur J Soil Biol 116:103488. https://doi.org/10.1016/j.ejsobi.2023.103488

Gomah SAA, Moustafa YTA, Fattah AAF, Batran AM (2020) The aptness of Nile tilapia pond sludge as a bedding media for earthworm growth and vermicompost production. Abbasa Int J Aquac 13:135–156

Görelşahin S, Yanar M, Kumlu M (2018) The effects of stocking density, *Tubifex* feeding and monosex culture on growth performance of guppy (*Poecilia reticulata*) in a closed indoor recirculation system. Aquaculture 493:153–157. https://doi.org/10.1016/j.aquaculture.2018.05.004

Gunadi B, Blount C, Edwards CA (2002) The growth and fecundity of *Eisenia fetida* (Savigny) in cattle solids pre-composted for different periods. Pedobiologia (Jena) 23:15–23

Gunya B, Masika PJ (2022) *Eisenia fetida* worm as an alternative source of protein for poultry : a review. Int J Trop Insect Sci 42:1–8. https://doi.org/10.1007/s42690-021-00531-6

Gunya B, Masika PJ, Hugo A, Muchenje V (2016) Nutrient composition and fatty acid profiles of oven-dried and freeze-dried earthworm *Eisenia foetida*. J Food Nutr Res 4:343–348. https://doi.org/10.12691/jfnr-4-6-1

Gupta SK, Fotedar R, Foysal MJ et al (2020) Impact of varied combinatorial mixture of non-fishmeal ingredients on growth, metabolism, immunity and gut microbiota of *Lates calcarifer* (Bloch, 1790) fry. Sci Rep 10:1–13. https://doi.org/10.1038/s41598-020-72726-9

Gusain R, Suthar S (2020) Vermicomposting of duckweed (*Spirodela polyrhiza*) by employing *Eisenia fetida*: changes in nutrient contents, microbial enzyme activities and earthworm biodynamics. Bioresour Technol 311:123585. https://doi.org/10.1016/j.biortech.2020.123585

Hamre K, Yúfera M, Rønnestad I et al (2013) Fish larval nutrition and feed formulation: knowledge gaps and bottlenecks for advances in larval rearing. Rev Aquac 5:S26-58. https://doi.org/10.1111/j.1753-5131.2012.01086.x

Haque MI mamun, Hasan M (2022) Optimization of culture media ingredient and inoculum on the yield of tubifex worms at pilot scale level. Dhaka Univ J Biol Sci 31:193–201. https://doi.org/10.3329/dujbs.v31i1.57928

Haque MM, Barua G (1989) Rearing of shingi (*Heteropneustes fossilis* Bloch) fry under laboratory conditions. II. Feeding and growth of fry. Bangladesh J Fish 12:67–72

Hasan M, Haque MIM, Akter N et al (2019) Effects of wetting media cattle blood, rice gruel and water on the yield and amino acid composition of tubificid worms. J Asiat Soc Bangladesh Sci 45(2):229–239. https://doi.org/10.3329/jasbs.v45i2.46596

Hashim R, Ali A, Saat NAM (1993) Supplementing artificial diets for catfish (*Glarias macrocephalus*) fry with tubifex. Pertanika J Trop Agric Sci 16(Suppl):37–40

Helena C, John A, Vinnerås B (2015) Vermicomposting as manure management strategy for urban small-holder animal farms–Kampala case study. Waste Manag 39:96–103. https://doi.org/10.1016/j.wasman.2015.02.009

Herawati VE, Nugroho RA, Hutabarat J, Karnaradjasa O (2016) Profile of amino acids, fatty acids, proximate composition and growth performance of *Tubifex tubifex* culture with different animal wastes and probiotic bacteria. AACL Bioflux 9:614–622

Herawati VE, Hutabarat J, Pinandoyo, Karna Radjasa O (2020) Growth performance of tilapia (*Oreochromis niloticus* Linnaeus, 1758) larvae with feeding *Tubifex tubifex* (Müller, 1774) from different fermentation of animal manures. Iran J Fish Sci 19:2039–2052. https://doi.org/10.22092/ijfs.2018.123936.1005

Holmstrup M, Hovvang MH, Slotsbo S (2020) Salinity of the growth medium is important for production potential and nutritional value of white worms (*Enchytraeus albidus* Henle). Aquac Res 51:2885–2892. https://doi.org/10.1111/are.14627

Holmstrup ME, Gadeberg SF, Engell-Sorensen K et al (2022) A new strategy in rearing of European flounder : using live *Enchytraeus albidus* to enhance juvenile growth. J Insects as Food Feed 1–9. https://doi.org/10.3920/JIFF2021.0106

Hoseinifar SH, Maradonna F, Faheem M et al (2023) Sustainable ornamental fish aquaculture: the implication of microbial feed additives. Animals. https://doi.org/10.3390/ani13101583

Hossain A, Rahman MS, Hasan M (2011) Optimum harvest for sustainable yield of fish live food tubificid worms. Dhaka Univ J Biol Sci 20:57–63

Hossain A, Mollah MFA, Hasan M (2012) Ratio optimisation of media ingredients for mass culture of tubificid worms (Oligochaeta, Tubificidae) in Bangladesh. Asian Fish Sci 25:357–368

Houndonougbo PK, Chikou A, Sodjinou E et al (2017) The effect of the incorporation of the flour of the worm of compost (*Eisenia foetida*) (Savigny, 1928) in the feed of tilapia *Oreochromis niloticus* high out in basin. Int J Fish Aquat Stud 5:6–12

Houndonougbo PK, Dalmeida A, Ouattara IN et al (2021) Use of fresh or dried manure worm (*Eisenia foetida*) on the growth performance of juvenile of *Clarias gariepinus* high out in basin. Int J Fish Aquat Stud 9:52–56. https://doi.org/10.22271/fish.2021.v9.i1a.2398

Hung TL, Tam MB, Cacot P, Lazard J (1999) Larval rearing of the Mekong catfish, *Pangasius bocourti* (Pangasiidae, Siluroidei): substitution of *Artemia* nauplii with live and artificial feed. Aquat Living Resour 12:229–232

Hung TL, Tuan AN, Cacot P, Lazard J (2002) Larval rearing of the Asian Catfish, *Pangasius bocourti* (Siluroidei, Pangasiidae): alternative feeds and weaning time. Aquaculture 212:115–127

Hussain SM, Arsalan MZH, Javid A et al (2018) Replacement of fish meal with *Moringa oleifera* leaf meal (MOLM) and its effect on growth performance and nutrient digestibility in *Labeo rohita* fingerlings. Pak J Zool 50. https://doi.org/10.17582/journal.pjz/2018.50.5.1825.1834

Jalbani S, Narejo NT, Khan P (2019) Rearing of catfish, *Rita rita* with live and prepared feeds in cemented cisterns. Pak J Zool 51:1–3. https://doi.org/10.17582/journal.pjz/2019.51.6.sc8

Jayalekshmi JN, Abraham KM, Sobhanakumar K (2017) Growth performance of angelfish, *Pterophyllum scalare* fed with different live worm diets. J Aquat Biol Fish 5:116–122

Jewel AS, Al MA, Amin R (2016) Comparative growth of tubificid worms in culture media supplemented with different nutrients. Int J Fish Aquat Stud 4:83–87

Jezierska-tys S, Frąc M, Tys J (2010) Microbiological hazards resulting from application of dairy sewage sludge: effects on occurrence of pathogenic microorganisms in soil. J Toxicol Environ Health A 73:1194–1201. https://doi.org/10.1080/15287394.2010.491777

Karabulut HA, Kurtoglu IZ, Yuksek T, Bayraktar Z (2020) The investigation of the possibility of using red California earthworm (*Eisenia fetida*) meal as an alternative protein source in rainbow trout (*Oncorhynchus mykiss*) diet. Fresenius Environ Bull 29:2951–2959. https://doi.org/10.35229/jaes.273810

Kasiri M, Farahi A, Sudagar M (2012) Growth and reproductive performance by different feed types in freshwater angelfish (*Pterophyllum scalare* Schultze, 1823). Vet Res Forum 3:175–179

Kauser H, Khwairakpam M (2022) Organic waste management by two-stage composting process to decrease the time required for vermicomposting. Environ Technol Innov 25:102193. https://doi.org/10.1016/j.eti.2021.102193

Kavle RR, Nolan PJ, Carne A et al (2023) Earth worming—an evaluation of earthworm (*Eisenia andrei*) as an alternative food source. Foods 12:1948

Khanom M, Rahman SM, Ali MY et al (2022) Effect of formulated feed as a substitute for live feed on growth performances, biochemical composition and digestive enzyme activities of asian stinging catfish, *Heteropneustes fossilis* (Bloch, 1794) Larvae. Adv Anim Vet Sci 10:1264. https://doi.org/10.17582/journal.aavs/2022/10.6.1264.1271

Kobayashi H, Ohtomi M, Sekizawa Y, Ohta N (2001) Toxicity of coelomic fluid of the earthworm Eisenia foetida to vertebrates but not invertebrates: probable role of sphingomyelin. Comp Biochem Physiol Part C: Toxicol Pharmacol 128:401–411. https://doi.org/10.1016/S1532-0456(00)00213-1

Kolesnyk N, Simon M, Marenkov O et al (2019) Oligochaetes (Oligochaeta): *Dero furcata*, sludge worm, *Enchytraeus albidus* and grindal worms as valuable food objects in fish farming (review). Ribogospodars'ka Nauk Ukraïni 1:28–47. https://doi.org/10.15407/fsu2019.01.028

Kostecka J, Pączka G (2006) Possible use of earthworm *Eisenia fetida* (Sav.) biomass for breeding aquarium fish. Eur J Soil Biol 42:231–233. https://doi.org/10.1016/j.ejsobi.2006.07.029

Kumar R, Gupta RK, Yadav R et al (2022) *Eisenia fetida* as protein source for growth enhancement of *Heteropneustes fossilis*. Egypt J Aquat Biol Fish 26:577–588. https://doi.org/10.21608/EJABF.2022.234553

Kumlu M, Beksari A, Eroldo OT et al (2018) DHA enrichment of the red earthworm *Eisenia fetida* for improving its potential as a dietary source for aquaculture. Aquaculture 496:10–18. https://doi.org/10.1016/j.aquaculture.2018.07.005

Lahnsteiner F, Lahnsteiner E, Duenser A (2023) Suitability of different live feed for first feeding of freshwater fish larvae. Aquac J 3:107–120. https://doi.org/10.3390/aquacj3020010

Langi S, Maulu S, Hasimuna OJ et al (2024) Nutritional requirements and effect of culture conditions on the performance of the African catfish (*Clarias gariepinus*): a review. Cogent Food Agric 10:2302642. https://doi.org/10.1080/23311932.2024.2302642

Li X, Zhao H, Gong M et al (2025) Thiamethoxam at environmentally relevant concentrations induces neurotoxicity in zebra fish larvae through binding with multiple receptors. Eco-Environment Heal 4:100133. https://doi.org/10.1016/j.eehl.2024.12.002

Lietz DM (1987) Potential for aquatic oligochaetes as live food in commercial aquaculture. Hydrobiologia 155:309–310. https://doi.org/10.1007/BF00025665

Lim CL, Dhert P, Sorgeloos P (2003) Recent developments in the application of live feeds in the freshwater ornamental fish culture. Aquaculture 227:319–331. https://doi.org/10.1016/S0044-8486(03)00512-X

Malla S, Banik S (2015) Larval rearing of an endangered catfish, *Ompok bimaculatus* (Bloch, 1794) with live and artificial diets : a preliminary study in Tripura, India. Int J Fauna Biol Stud 2:16–21

Mandal RN, Kar S, Chattopadhyay DN et al (2016) *Tubifex* production using agro-industrial wastes and raw cattle dung. J Appl Aquac 28:70–75. https://doi.org/10.1080/10454438.2016.1169729

Marian MP, Pandian TJ (1984) Culture and harvesting techniques for *Tubifex tubifex*. Aquaculture 42:303–315

Marsh L, Subler S, Mishra S, Marini M (2005) Suitability of aquaculture effluent solids mixed with cardboard as a feedstock for vermicomposting. Bioresour Technol 96:413–418. https://doi.org/10.1016/j.biortech.2004.06.002

Mashur M, Bilad MR, Hunaepi H, Huda N (2021) Formulation of organic wastes as growth media for cultivation of earthworm nutrient-rich *Eisenia foetida*. Sustainability 13:10322

Mathew RT, Debnath S, Kundu P et al (2022) Growth and survival of goldfish (*Carassius auratus*) juveniles fed tubifex, custard meal and commercial feeds. Sci J King Faisal Univ 23:6. https://doi.org/10.37575/b/vet/210080

McKay W, Jeffs A (2022) Comparison of three artificial diets for the larviculture of giant kōkopu (*Galaxias argenteus*). Fishes 7:310. https://doi.org/10.3390/fishes7060310

McKay W, Jeffs A (2023) Optimization of *artemia* feed regimes for larval Giant Kōkopu (*Galaxias argenteus*). Fishes 8:183. https://doi.org/10.3390/fishes8040183
Memi D, Çelikkale MS, Ercan E (2004) The effect of different diets on the white worm (*Enchytraeus albidus* Henle, 1837) Reproduction. Turkish J Fish Aquat Sci 07:5–7
Memiş D, Çelikkale MS, Ercan E (2004) The Effect of Different Diets on the White Worm (Enchytraeus albidus Henle, 1837)Reproduction. Turkish J Fish Aquat Sci 07: 5–7. https://dergipark.org.tr/en/download/article-file/141995
Mi J, Lu R, Yan X et al (2022) Evaluating the mixture of earthworm meal and wormcast as a protein source for common carp (Cyprinus carpio L.) based on growth performance, antioxidant, immune capacity, lipid metabolism and intestinal health. Aquac Reports 24:101118. https://doi.org/10.1016/j.aqrep.2022.101118
Mohanta KN, Subramanian S (2002) Effect of diets with protein from different sources on the growth of goldfish, *Carassius auratus*. Isr J Aquac 54:134–140
Mohanta KN, Subramanian S, Korikanthimath VS (2013) Evaluation of different animal protein sources in formulating the diets for blue gourami, *Trichogaster trichopterus* fingerlings. J Aquac Res Dev 4:1–7. https://doi.org/10.4172/2155-9546.1000164
Mohanta KN, Subramanian S, Korikanthimath VS (2016) Potential of earthworm (*Eisenia foetida*) as dietary protein source for rohu (*Labeo rohita*) advanced fry. Cogent Food Agric 2:1138594. https://doi.org/10.1080/23311932.2016.1138594
Mohideen AKS, Sheriff MA, Altaff K (2014) Effect of three different feeds on the growth and survival of sailfin molly *Poecilia latipinna* (Lesueur, 1821). Revel Sci 04:45–48
Mohideen AKS, Altaff K (2021) Influence of different types of diets on the growth performance of juvenile guppies (Poecilia reticulata Peters, 1859). Jurnal Mangifera Edu 5:93–102. https://doi.org/10.31943/mangiferaedu.v5i2.105
Mollah MFA, Mosharaf K, Mariom (2012) Selection of suitable media and intervals of media inoculation for culturing Tubificid worms. J Bangladesh Agric Univ 10:325–330
Moroasui MY, Ampofo-Yeboah A, Antwi MA (2022) Effects of feeding pellets, live earthworms and tilapia on the growth of African sharptooth catfish fingerlings. S Afr J Anim Sci 52:186–194. https://doi.org/10.4314/sajas.v52i2.8
Mugwanya M, Mahmoud AOD, Fahad K, Hani S (2022) Replacement of fish meal with fermented plant proteins in the aquafeed industry: a systematic review and meta-analysis. Rev Aquac 0–27. https://doi.org/10.1111/raq.12701
Munnoli PM, Bhosle S (2009) Effect of soil and cow dung proportion on vermi-composting by deep burrower and surface feeder species. J Sci Ind Res (India) 68:57–60
Musyoka SN, Liti DM, Ogello E, Waidbacher H (2019) Utilization of the earthworm, *Eisenia fetida* (Savigny, 1826) as an alternative protein source in fish feeds processing : a review. Aquac Rese 50:2301–2315. https://doi.org/10.1111/are.14091
Musyoka SN, Liti D, Ogello EO et al (2020a) Earthworm, *Eisenia fetida*, bedding meal as potential cheap fishmeal replacement ingredient for semi-intensive farming of Nile Tilapia, *Oreochromis niloticus*. Aquac Res 51:2359–2368. https://doi.org/10.1111/are.14579
Musyoka SN, Liti DM, Ogello EO et al (2020b) Using earthworm, *Eisenia fetida*, to bio-convert agro-industrial wastes for aquaculture nutrition. BioResour 15:574–587
Muziasari WI, Pitkänen LK, Sørum H et al (2017) The resistome of farmed fish faeces contributes to the enrichment of antibiotic resistance genes in sediments below Baltic Sea fish farms. Front Microbiol 7:1–10. https://doi.org/10.3389/fmicb.2016.02137
Narciso A, Barra Caracciolo A, De Carolis C (2023) Overview of direct and indirect effects of antibiotics on terrestrial organisms. Antibiotics 12:1471. https://doi.org/10.3390/antibiotics12091471
Nath S, Samanta S, Podder R, Weltje L (2022) Ex-situ evaluation of chironomid larvae as a potential supplementary food in aquaculture. Proc Natl Acad Sci India Sect B Biol Sci 92:801–806. https://doi.org/10.1007/s40011-022-01377-9
Negi R, Suthar S (2018) Degradation of paper mill wastewater sludge and cow dung by brown-rot fungi *Oligoporus placenta* and earthworm (*Eisenia fetida*) during vermicomposting. J Clean Prod 201:842–852. https://doi.org/10.1016/j.jclepro.2018.08.068
Ngosong C, Nfor I, Tanyi C et al (2020) Effect of poultry manure and inorganic fertilizer on earthworm population and soil fertility: implication on root nodulation and yield of climbing bean (*Phaseolus vulgaris*). Fundam Appl Agric 1. https://doi.org/10.5455/faa.76612
Nica A, Petrea MS, Mogodan A et al (2020) The effect of food type (natural vs. formulated diet) on growth performance and coloration of juvenile Japanese ornamental carp (Koi, Cyprinus carpio L.). Sci Pap Ser D Anim Sci LXIII:528–533

Nkontcheu DBK, Fotio AL, Kenfack AD et al (2023) Ecological risk assessment of pesticides based on earthworms in soils on the southeast slopes of Mount Cameroon. Soil & Environmental Health 1(4):100047. https://doi.org/10.1016/j.seh.2023.100047

Novriadi R, Spangler E, Rhodes M et al (2017) Effects of various levels of squid hydrolysate and squid meal supplementation with enzyme-treated soy on growth performance, body composition, serum biochemistry and histology of Florida pompano *Trachinotus carolinus*. Aquaculture 481:85–93. https://doi.org/10.1016/j.aquaculture.2017.08.032

Nuswantoro S, Sugianto S, Rahardjo P (2018) Effect of using silkworm (*Tubifex* sp.) living on the survival rate and growth of the catfish larvae (*Clarias* sp.). J Agric Vet Sci 11:42–46. https://doi.org/10.9790/2380-1102024246

Onura CN, James GJ, Muthumbi AW et al (2022) Performance of African catfish *Clarias gariepinus* larvae fed on formulated diets containing *Spirulina platensis* and *Eisenia fetida*. East African J Sci Technol Innov 3:1–21

Oplinger RW, Bartley M, Wagner EJ et al (2011) Culture of *Tubifex tubifex*: effect of feed type, ration, temperature, and density on juvenile recruitment, production, and adult survival. N Am J Aquac 73:68–75. https://doi.org/10.1080/15222055.2010.549028

Panikkar P, Ayyar SP, Shakuntala K (2010) Utilisation of *Tubifex* worms by *Macrobrachium lanchesteri* (de Man) under different feeding regimes. Indian J Fish 57:81–84

Panjgotra S, Sangha GK, Sharma S, Kondal JK (2016) Effect of wheat straw and FYM on growth and reproduction of *Eisenia fetida* during vermicomposting. J Appl Nat Sci 8:2212–2218

Parente CE, Oliveira E, Fernandes S et al (2021) Fluoroquinolone-contaminated poultry litter strongly affects earthworms as verified through lethal and sub-lethal evaluations. Ecotoxicol Environ Saf 207:111305. https://doi.org/10.1016/j.ecoenv.2020.111305

Parveen N, Mondal P, Raja K et al (2024) Phytotoxicity of trihalomethanes and trichloroacetic acid on *Vigna radiata* and *Allium cepa* plant models. Environ Sci Pollut Res 5100–5115. https://doi.org/10.1007/s11356-023-31419-2

Pelosi C, Bertrand C, Daniele G et al (2021) Residues of currently used pesticides in soils and earthworms: a silent threat ? Agric Ecosyst Environ 305:107167. https://doi.org/10.1016/j.agee.2020.107167

Pereira JO, Gomes EF (1995) Growth of rainbow trout fed a diet supplemented with earthworms, after chemical treatment. Aquacult Int 3:36–42

Pilot AI, Sumi KR, Sharker MR et al (2014) Effect of different live feeds on the growth performance and flesh quality of Nile tilapia (*Oreochromis niloticus*) fingerlings. Int J Life Sci Biotechnol Pharma Res 3:182–188

Pritzkow S, Morales R, Camacho M, Soto C (2021) Uptake, retention, and excretion of infectious prions by experimentally exposed earthworms. Emerg Infect Dis 27:3151–3154. https://doi.org/10.3201/eid2712.204236

Putra DF, Nur F, Rahimi SAE, Othman N (2019) Effects of different live feed on growth and survival rate of clown loach, *Cromobotia macracantus*. IOP Conference Series: Earth and Environmental Science, vol 348. IOP Publishing, p 012099. https://doi.org/10.1088/1755-1315/348/1/012099

Radhakrishnan G, Shivlumar MVS et al (2020) Dietary protein requirement for maintenance, growth, and reproduction in fish : a review. J Entomol Zool Stud 8:208–215

Rahman MA, Bhadra A, Begum N, Hussain MG (1997) Effects of some selective supplemental feeds on the survival and growth of catfish (*Clarias batrachus* Lin.) fry. Bangladesh J Fish Res 1:55–58

Randal KB, Doroshov SI (1984) Feeding trials with hatchery produced white sturgeon juveniles (*Acipenser transmontanus*). Aquaculture 36:237–243

Ravindran B, Dinesh SL, Kennedy LJ (2008) Vermicomposting of solid waste generated from leather industries using epigeic earthworm *Eisenia foetida*. Appl Biochem Biotechnol 151:480–488. https://doi.org/10.1007/s12010-008-8222-3

Rawat P, Biswas P, Jena AK et al (2018) Effect of dietary incorporation of natural attractants on growth and survival during seed rearing of Indian butter catfish, *Ompok bimaculatus*. J Environ Biol 40:661–667

Remize M, Brunel Y, Silva JL et al (2021) Microalgae n-3 PUFAs production and use in food and feed industries. Mar Drugs 19:1–29. https://doi.org/10.3390/MD19020113

Rojas I, Cárcamo CB, Defranchi Y et al (2023) A diet rich in HUFAs enhances the energetic and immune response capacities of larvae of the scallop *Argopecten purpuratus*. Animals. https://doi.org/10.3390/ani13081416

Ronyai A, Feledi T (2012) Co-feeding as a weaning procedure in sterlet (*Acipenser ruthenus* L.) larvae. Aquac Res 1:10–13. https://doi.org/10.1111/j.1365-2109.2012.03167.x

Ruby P, Antony C, Ahilan B, Selvaraj S (2024) White worms enchytraeus albidus as a live feed and formulated aquafeeds. Vigyan Varta: Int J E-Magazine Sci 5:165–167

Rufchaei R, Hoseinifar SH, Nedaei S et al (2019) Non-specific immune responses, stress resistance and growth performance of Caspian roach (*Rutilus caspicus*) fed diet supplemented with earthworm (*Eisenia foetida*) extract. Aquaculture 511:734275. https://doi.org/10.1016/j.aquaculture.2019.734275

Russio CSP, Cardoso IL, Ferri GH, et al (2022) Use of earthworm (*Eisenia fetida*) meal as a supplement for feeding tilapia juveniles (*Oreochromis niloticus*). Int J Sci Res Updat 1–6

Saha MK, Patra BC (2013) Effect of growth and pigmentation on acceptability of different feeds by *Colisa lalia* (Hamilton, 1822). J Adv Lab Res Biol 4:97–99

Şahİn D, Öz M, Karsli Z et al (2017) Effect of frozen white worm (Enchytraeus sp) on growth of platy (Xiphophorus maculatus Gunther, 1866). Turkish J Aquat Sci 32:71–75. https://doi.org/10.18864/TJAS201706

Sakthika T, Ronald J, V SK, Felicitta J (2014) Growth of *Mystus montanus* fed with two different earthworm meal. Int J Environ Sci 4:551–557. https://doi.org/10.6088/ijes.2014040400010

Salamanca N, Herrera M (2025) Amino acids as dietary additives for enhancing fish welfare in aquaculture. Animals 15:1293

Saleh R, Burri L, Benitez-Santana T et al (2018) Dietary krill meal inclusion contributes to better growth performance of gilthead seabream juveniles. Aquac Res 49:3289–3295. https://doi.org/10.1111/are.13792

Santiago CB, Lovell RT (1988) Amino acid requirements for growth of Nile tilapia. J Nutr 118:1540–1546

Saravanan R, Samyappan K, Gnanavel K, Purushothaman K (2015) Studies on the nutritive value and fatty acid contents in fingerlings of *Catla catla* fed on traditional diet and freeze dried Tuifex. Int J Inf Res Rev 25:726–733

Sarkar UK, Lakra W, Deepak PK et al (2006) Performance of different types of diets on experimental larval rearing of endangered *Chitala chitala* (Hamilton) in recirculatory system. Aquaculture 261:141–150. https://doi.org/10.1016/j.aquaculture.2006.06.051

Sarkar UK, Deepak PK, Negi RS et al (2007) Efficacy of different types of live and non-conventional diets in endangered clown knife fish *Chitala chitala* (Hamilton-Buchanan) during its early life stages. Aquac Res 38:1404–1410. https://doi.org/10.1111/j.1365-2109.2007.01803.x

Sathya R, Deivanayaki M (2015) Reproduction influence of the earthworm, *Eisenia fetida* cultured in different media of green gram waste. Int Hournal Species 14:29–39

Saurabh S, Sridhar N, Gangadhar B et al (2013) Growth performance of fry of the black-spot barb *Puntius filamentosus* (Valenciennes, 1844) fed live feeds and artificial feed. Indian J Fish 60:137–140

Seidgar M, Hafezieh M, Dadgar S et al (2022) The comparison of growth, survival rate and behavior of Oscar fish (*Astronauts ocellatus*) fries fed by *Artemia urmiana*, earthworm and beef heart supplemented diets. J Surv Fish Sci 8:49–62. https://doi.org/10.18331/SFS2022.8.3.4

Shahjahan M, Taslima K, Rahman MS et al (2022) Effects of heavy metals on fish physiology–a review. Chemosphere 300:134519. https://doi.org/10.1016/j.chemosphere.2022.134519

Sharma S, Tuladhar R, Basnet Y, Manandhar S, Bhattarai S, Singh A, Varma A (2019) Effect of substrates on azotobacter chroococcum-enriched vermicompost for growth of phaseolus. In: Sayyed R (ed) Plant growth promoting rhizobacteria for sustainable stress management. Microorganisms for sustainability, vol 13. Springer, Singapore, pp 37–45. https://doi.org/10.1007/978-981-13-6986-5_2

Sicuro B, Castelar B, Bergamino C et al (2023) Freshwater mussel meal as new alternative ingredient for rainbow trout (*Oncorhynchus mykiss*) feeds: growth performance and histomorphological analyses. Aquacult Int. https://doi.org/10.1007/s10499-023-01168-7

Singh D, Suthar S (2012) Vermicomposting of herbal pharmaceutical industry waste : earthworm growth, plant-available nutrient and microbial quality of end materials. Bioresour Technol 112:179–185. https://doi.org/10.1016/j.biortech.2012.02.101

Singh RK, Vartak VR, Chavan SL et al (2010) Management of waste organic matters and residential used water for culture and biomass production of red worm (*Tubifex tubifex*). Int J Environ Waste Manag 5:140–151. https://doi.org/10.1504/IJEWM.2010.029698

Solang J, Pangkey H, Wullur S, Lantu S (2014) Ratio of c:n in culture media of silk worm, *Tubifex* sp. Aquat Sci Manag 2(1):19. https://doi.org/10.35800/jasm.2.1.2014.12391

Sontakke R, Shekhar C, Saharan N et al (2019) Growth response, digestive enzyme activity and stress enzyme status in early stages of an endangered fish, *Notopterus chitala* (Hamilton, 1822) fed with live feed and formulated diet. Aquaculture 510:182–190. https://doi.org/10.1016/j.aquaculture.2019.05.042

Suthar S, Pandey B, Gusain R, Gaur RZ (2017) Nutrient changes and biodynamics of *Eisenia fetida* during vermicomposting of water lettuce (*Pistia* sp.) biomass: a noxious weed of aquatic system. Environ Sci Pollut Res 24:199–207. https://doi.org/10.1007/s11356-016-7770-2

Syamsunarno MB, Sunarno MTD (2022) Response of post-larva of snakehead (*Channa striata*) to feeding dried silkworm (*Tubifex* sp.) and artificial diet. Depik 11:16–22. https://doi.org/10.13170/depik.11.1.23103

Syandri H, Azrita, Niagara, Junaidi (2015) Preliminary study on the feeding schedule of laboratory reared of bonylip barb larva, *Osteochilus vittatus* Cyprinidae. Aquac Res Dev 6:1–4. https://doi.org/10.4172/2155-9546.1000368

Tacon AGJ, Stafford EA, Edwards CA (1983) A preliminary investigation of the nutritive value of three terrestrial lumbricid worms for rainbow trout. Aquaculture 35:187–199. https://doi.org/10.1016/0044-8486(83)90090-X

Tadesse Z, Adugna M, Yimer A (2021) Partial replacement of fish meal with earth worm (Eisenia Fetida S.) meal in the diet of African Catfish (Clarias gariepinus L.) fingerlings. In: Livestock research results, vol 9. Addis Ababa, p 663

Tamilarasu A, Nethaji M, Bharathi S et al (2020) Significance of white worm in aquaculture as a source of protein-rich live feed. Biot Res Today 2:1298–1301

Thongprajukaew K, Kovitvadhi U, Kovitvadhi S et al (2013) Evaluation of growth performance and nutritional quality of diets using digestive enzyme markers and in vitro digestibility in Siamese fighting fish (*Betta splendens* Regan, 1910). Afr J Biotechnol 12:1689–1702. https://doi.org/10.5897/AJB12.2051

Tosun DD, Simsar M (2018) Effects of live food feeding on growth performance and some histological parameters of *Herotilapia multispinosa* and *Amatitlania nigrofasciata*. Aquat Sci Eng 33:131–137. https://doi.org/10.26650/ASE201818018

Tripathi G, Bhardwaj P (2004a) Comparative studies on biomass production, life cycles and composting efficiency of *Eisenia fetida* (Savigny) and *Lampito mauritii* (Kinberg). Bioresour Technol 92:275–283. https://doi.org/10.1016/j.biortech.2003.09.005

Tripathi G, Bhardwaj P (2004b) Decomposition of kitchen waste amended with cow manure using an epigeic species (*Eisenia fetida*) and an anecic species (*Lampito mauritii*). Bioresour Technol 92(2):215–218. https://doi.org/10.1016/j.biortech.2003.08.013

Truong HH, Hines BM, Rombenso AN, Simon CJ (2023) Aquaculture nutrition in Australia: challenges and trends. Anim Prod Sci. https://doi.org/10.1071/AN23078

Vartak VR, Singh RK (2009) Effects of live food organisms and formulated diets on growth, survival, and body protein of Asian sea bass fry (*Lates calcarifer*, Bloch). Isr J Aquac-Bamidgeh 6:63–67

Vasagam KPK, Shanmugam A, Rajagopal S (2007) Dietary effect on fry production and growth performance of sailfin molly, *Poecilia latipinna*, in salt water. Acta Ichthyol Piscat 37:29–35

Verhoef GD, Jones PL, Austin CM (1998) A comparison of natural and artificial diets for juveniles of the Australian freshwater crayfish *Cherax destructor*. J World Aquac Soc 29:243–248

Vital VDJ, Kpogue Diane NS, Apollinaire MG, Didier FE (2016) Culture of earthworm (*Eisenia fetida*), production, nutritive value and utilization of its meal in diet for *Parachanna obscura* fingerlings reared in captivity. Int J Fish Aquat Stud 4:1–5

Walsh ML, Fairchild EA, Rennels N, Howell WH (2015a) The effects of live and artificial diets on feeding performance of winter flounder, *Pseudopleuronectes americanus*, in the hatchery. J World Aquac Soc 46:61–68. https://doi.org/10.1111/jwas.12171

Walsh ML, Fairchild EA, Rennels N, Howell WH (2015b) The effects of live and artificial diets on feeding performance of cultured winter flounder, *Pseudopleuronectes americanus*, in the wild: survival, feeding, growth, and nucleic acid analyses. J World Aquac Soc 46:461–474. https://doi.org/10.1111/jwas.12210

Wang BC, Ma J, Xu Q et al (2015) Effects of different food on growth and survival of first-feeding taimen *Hucho taimen* (Pallas, 1773) larvae. J Appl Ichthyol 31:337–342. https://doi.org/10.1111/jai.12663

Wang L, Yin N, Sagada G et al (2020) Partial replacement of fishmeal with corn gluten meal, pea protein isolate and their mixture in diet of black sea bream (*Acanthopagrus schlegelii*) juveniles: effects on growth performance, feed utilization and haematological parameters. Aquac Res 51:2071–2083. https://doi.org/10.1111/are.14558

Wang C, Song Y, Liang J et al (2024) Antibiotic resistance genes are transferred from manure-contaminated water bodies to the gut microbiota of animals through the food chain. Environ Pollut 363:125087. https://doi.org/10.1016/j.envpol.2024.125087

Xing S, Liang X, Zhang X et al (2024) Essential amino acid requirements of fish and crustaceans, a meta-analysis. Rev Aquac 16:1069–1086. https://doi.org/10.1111/raq.12886

Xu T, Fei F, Ding Y et al (2021) Study on the comprehensive utilization of solid residues of *Flammulina velutipes* and vinegar and their application as feed in *Eisenia fetida* earthworm culture. Environ Sci Pollut Res 28:49153–49165

Yang S, Du J, Luo J et al (2019) Effects of different diets on the intestinal microbiota and immunity of common carp (*Cyprinus carpio*). J Appl Microbiol 127:1327–1338. https://doi.org/10.1111/jam.14405

Yanık T, Kocaman EM, Pirol A, Mammadov J (2017) Evaluation effects of addition of white worm (*Enchytraeus albidus* Henle, 1837) to diets on growth of brown trout fry (*Salmo trutta fario* L.). Curr Trends Nat Sci 6:272–276

Yazid MHD, Djunaidah IS, Nurhudah M (2021) Growth performance of silkworms (*Tubifex* sp.) cultivated using a dry substrate. J Perikan Univ Gadjah Mada 24:101–107. https://doi.org/10.22146/jfs.68259

Zakaria Z, Salleh NHM, Mohamed AR et al (2012) Optimization of protein content in earthworm-based fish feed formulation for catfish (*Clarius gariepinus*). Sains Malays 41:1071–1077

Zazouli MA, Hezarjaribi HZ, Charati JY et al (2021) Investigating the effects of vermicomposting process using *Eisenia fetida* earthworms on the reduction of parasites population. J Environ Health Sci Eng 19:1623–1633. https://doi.org/10.1007/s40201-021-00718-6

Zhao L, Luo J, Liu Q et al (2020) Different diets can affect the digestion and immunity of common carp (*Cyprinus carpio*) according to enzyme activity assay and transcriptome sequencing. Aquaculture 523:735176. https://doi.org/10.1016/j.aquaculture.2020.735176

Zhao F, Yang L, Li G et al (2022) Veterinary antibiotics can reduce crop yields by modifying soil bacterial community and earthworm population in agro-ecosystems. Sci Total Environ 808:152056. https://doi.org/10.1016/j.scitotenv.2021.152056

Zhou M, Xu Y, Ouyang P et al (2020) Evolution and distribution of resistance genes and bacterial community in water and biofilm of a simulated fish-duck integrated pond with stress. Chemosphere 245:125549. https://doi.org/10.1016/j.chemosphere.2019.125549

Authors and Affiliations

Muziri Mugwanya[1] · Mahmoud A. O. Dawood[1] · Hani Sewilam[1,2]

✉ Hani Sewilam
sewilam@lfi.rwth-aachen.de

Muziri Mugwanya
muziri@aucegypt.edu

Mahmoud A. O. Dawood
mahmoud-dawood@aucegypt.edu

1 Center for Applied Research On the Environment and Sustainability, School of Science and Engineering, The American University in Cairo, AUC Avenue, P.O. Box 74, New Cairo 11835, Egypt

2 UNESCO Chair in Hydrological Changes and Water Resources Management, RWTH Aachen University, Aachen, Germany