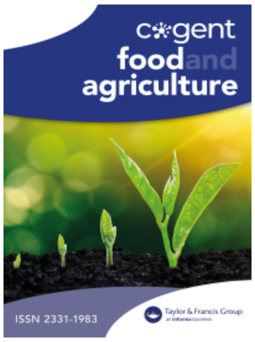

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Growth, feed utilization and digestibility of *Oreochromis shiranus* (Boulenger 1905) fed dietary yellow mealworm larvae (*Tenebrio molitor)* meal raised in earthen ponds

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ABSTRACT
This study investigated the effects of incorporating yellow mealworm larvae (*Tenebrio molitor*) on the growth, feed utilization, and digestibility of *Oreochromis shiranus*, a dominant aquaculture species in Malawi. Four isonitrogenous diets were formulated by replacing fishmeal with yellow mealworms at 0%, 25%, 50%, and 75%. The formulated feed was fed to 720 fingerlings (15.05 ± 2 g) for 126 days in 12 experimental concrete ponds for the growth trial. A digestibility trial was conducted with 240 juveniles (49.63 ± 1.68g) fed for 40 days in 12 150 L tanks, followed by biochemical analysis. Results showed that replacing fishmeal with yellow mealworm had no significant effect on the final average body weight, weight gain, specific growth rate, feed intake, apparent feed conversion ratio, and survival rate of *O. shiranus* fingerlings. However, a significant difference in hepatosomatic indices was observed, though effect size was small. Apparent digestibility coefficients for dry matter, ash, and crude fat were higher for diets with yellow mealworm inclusion than diet with fishmeal only ($p < 0.05$). In contrast, the inclusion of yellow mealworm did not affect the digestibility of crude protein or gross energy. These findings suggest that yellow mealworm larvae can replace up to 75% of fishmeal without compromising growth and feed utilization of *O. shiranus*.

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1. Introduction

Globally, aquaculture production is on the rise; however, in many developing countries, it is not practiced to its full potential (FAO., 2024; Mussa et al., 2020). This is largely attributed to limited technical capacity and poor feed quality, which hinder growth in the sector (FAO., 2024; Langi et al., 2024). In Malawi, aquaculture production is estimated at approximately 10,000 metric tons annually, contributing only 5% to total fish production (Government of Malawi, 2023). Government and international organizations have promoted sustainable aquaculture to enhance production, income, food security, and nutrition (CASA, 2020). While these efforts have increased the number of fish farmers, production remains low and has not kept pace (Government of Malawi, 2023). According to Munthali et al. (2022), one major constraint limiting fish production in Malawi is the availability of high-quality feed. When feed is available, it is often prohibitively expensive, making it inaccessible to small-scale farmers (Munthali et al., 2022). This is particularly true for floating feed, which is well suited for commercial production but remains out of reach for most small-scale farmers in the country.

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To address this, fishmeal has been promoted as a superior protein source for aquafeed production (Kim & Cho, 2024). In Malawi, fishmeal is predominantly derived from small-sized *Engraulicypris sardella* (Usipa), a species which is abundant in Lake Malawi (Simfukwe et al., 2022, 2024). However, the use of *E. sardella* for fishmeal has sparked conflict, as it is a vital protein source for the country's poor population (Simfukwe et al., 2024; Simmance et al., 2022). This dual demand for *E. sardella* for human consumption and use in aquafeeds has made fishmeal expensive and created competing interests among stakeholders. Moreover, the reliance on natural fish resources for fishmeal contradicts the principles of the Blue Transformation framework, which seeks to ensure the sustainable and equitable use of aquatic resources (FAO, 2024). Overharvesting *E. sardella* for fishmeal risks further depleting natural fish stocks and worsening food insecurity among vulnerable populations. Hence, many farmers resort to low-cost agricultural by-products such as rice bran, maize bran, and local vegetables for fish feed (Rana et al., 2009). Although these alternatives are affordable, they are nutritionally inferior and result in low fish production (Munguti et al., 2024). Hence, researchers have explored plant and animal protein alternatives to fishmeal in aquafeeds (Egerton et al., 2020; Voorhees et al., 2019). Legume based plant sources such as soybean have been widely promoted (Maulu et al., 2022; Yi et al., 2016). However, their inferiority in nutritional profile, anti-nutritional factors, and competition with humans limits their optimal applications (Voorhees et al., 2019).

As a result, insects have emerged as a promising alternative protein source for animal feed, offering benefits for both human livelihoods and the natural environment (El-Ouny et al., 2023; Maulu et al., 2022; Ngoepe et al., 2024). Moreover, insect protein production has lower manufacturing costs and a smaller environmental impact compared to fishmeal (Chen et al., 2023; Maulu et al., 2022). The transition toward insect-based proteins in aquafeeds is driven by the need to reduce the carbon footprint associated with traditional feed ingredients (Willora et al., 2025). Among the insect species studied for aquaculture, the black soldier fly (*Hermetia illucens*) and mealworm (*Tenebrio molitor*) are the most researched and promising alternatives to fishmeal (Maulu et al., 2022; Willora et al., 2025). Notably, yellow mealworms meet all nutritional requirements for fish growth, and their larva-derived protein meal has a competitive nutritional profile compared to fishmeal (Anany et al., 2025). Yellow mealworms are easy to raise and feed, and they can recycle nutrients from organic waste, such as manure, generating biomass efficiently (Anany et al., 2025). This practice contributes to environmental conservation by reducing greenhouse-gas emissions and mitigating ecological degradation (Willora et al., 2025). Hence, they can be reared using conventional mass rearing for commercial production (Shah et al., 2024).

The potential of yellow mealworm larvae to enhance fish growth, digestibility, and health in *Oreochromis niloticus* (Nile tilapia) has been documented by Anany et al. (2025) and El-Desouky et al. (2024), while Zhang et al. (2023) reported its benefits in improving Nile tilapia flesh quality. However, there is limited research on the potential of yellow mealworm larvae to improve fish growth, performance, and digestibility of *Oreochromis shiranus* in Malawi. *O. shiranus* is the most commonly farmed fish species in Malawi, and is valued for its high nutritional content, fresh taste, and adaptability (Government of Malawi, 2023; Munthali et al., 2022). Approximately 10,000 fish farmers cultivate *O. shiranus*, accounting for 75% of Malawi's annual aquaculture production (Government of Malawi, 2023). However, the species has a slow growth rate, typically reaching only 200–400 g within six months (Government of Malawi, 2023; Munthali et al., 2022). This slow growth is often attributed to the use of poor-quality feeds and the high cost of floating feeds, which limit their accessibility to farmers (Munthali et al., 2022). Yellow mealworm larvae offer a promising alternative protein source for addressing these challenges. Their protein content was comparable to fishmeal, reaching up to 65% (Makkar et al., 2014). However, the effect of replacing fishmeal with yellow mealworm larvae as the primary protein source on the growth performance of *O. shiranus* remains unclear. Therefore, this study analyzed the growth and digestibility response of *O. shiranus* exposed to diets with varying replacement levels of fishmeal with yellow mealworm larvae meal at 0%, 25%, 50%, and 75% to fill the research gap. We hypothesized that the inclusion of yellow mealworm larvae meal in the diet of *O. shiranus* would have no significant effect on growth performance, feed utilization, digestibility, or water quality parameters.

2. Materials and methods

2.1. Experimental diets formulation

The experiment was conducted at the Aquaculture and Fisheries Department of Lilongwe University of Agriculture and Natural Resources (LUANAR), Bunda Campus, an African Center of Excellence in Aquaculture and Fisheries in Lilongwe, Malawi. Four iso-nitrogenous diets were formulated with yellow mealworms incorporated at levels of 0%, 8.5%, 17.5%, and 26.5%, replacing fish meal protein at rates of 35.4%, 26.5%, 17.5%, and 8.5% in diets 1, 2, 3, and 4, respectively (Table 1). The feed replacement levels were set at 0% (control diet), 25% (Diet 2), 50% (Diet 3), and 75% (Diet 4). The ingredients were thoroughly blended and water was added to form a paste. This paste was processed using a pelleting machine with a 2.5 mm die. The pellets were air-dried indoors and broken into small pieces suitable for feeding fish. To ensure freshness and prevent feed deterioration, pellets were prepared in smaller batches of 1 kg each for growth trials.

2.2. Proximate composition analysis

Proximate composition analysis was conducted on ingredients, formulated diets (Table 2), and fish samples (Table 4) following AOAC (2002) guidelines, using 2 g of each sample. Moisture content was determined by drying samples in a hot-air oven at 105 °C for 5 hours (DV-6000, Yamato Scientific Co. Ltd., Tokyo, Japan), followed by cooling in a desiccator (DES-830, Yamato Scientific Co. Ltd., Tokyo, Japan). Ash content was measured by incineration in a muffle furnace (FM48, Yamato Scientific Co. Ltd., Tokyo, Japan) at 550 °C for 5 hours. Crude protein was determined via the Kjeldahl method, using 2 g samples digested with 1 tablet Kjeltabs (Cu/3.5) and 25 ml of 98% H_2SO_4, heated at 150 °C for 30 minutes and then at 400 °C until the solution turned green. Total nitrogen was converted to crude protein using a factor of 6.25 (Mphande & Chama, 2015). Crude fat was assessed by Soxhlet extraction, and crude fiber was measured by acid-base hydrolysis of ether-extracted residues, followed by ashing at 550 °C and calculated from weight loss. Gross energy was estimated using an oxygen bomb calorimeter (Model 6200; Parr Instrument Co.) with 0.6 g samples combusted under 30 atm oxygen pressure. All analyses were done in triplicate.

Table 1. Ingredient composition % as replacement of quantities of fishmeal in the diets.

	Replacement levels			
Ingredients	Diet 1 (0%)	Diet 2 (25%)	Diet 3 (50%)	Diet 4 (75%)
Soybean	40.4	40.5	40.5	40.5
Fishmeal	35.4	26.5	17.5	8.5
Yellow mealworms	0	8.5	17.5	26.5
Maize	9.4	9.5	9.5	9.5
Cassava	1.4	1.5	1.5	1.5
Wheat bran	10.4	10.6	10.6	10.6
Lysine	0.5	0.5	0.5	0.5
DL Methionine	0.5	0.5	0.5	0.5
Limestone	0.5	0.5	0.5	0.5
Mono-calcium Phosphate	0.5	0.5	0.5	0.5
Tilapia premix	0.5	0.5	0.5	0.5
Vitamin and mineral premix	0.5	0.5	0.5	0.5
Crude protein (%)	34	34	34	34

Note: Mineral premix consisted of, iron, zinc, copper, cobalt. Vitamin premix consist of vitamin C, vitamin B1, vitamin B12, Vitamin A, vitamin D3, vitamin E, Niacin, pantothenic acid and folic acid.

Table 2. Proximate composition (mean ± SE) of each of the formulated growth diets.

	Replacement diet levels			
Proximate parameters	Diet 1 (0%)	Diet 2 (25%)	Diet 3 (50%)	Diet 4 (75%)
Dry matter (%)	26.89 ± 0.87	25.95 ± 0.05	27.45 ± 0.32	24.91 ± 0.26
Ash (%)	7.14 ± 0.45	5.73 ± 0.06	5.88 ± 0.11	5.47 ± 0.21
Crude fat (%)	8.34 ± 0.20	8.55 ± 0.25	9.18 ± 0.14	9.41 ± 0.17
Crude protein (%)	30.45 ± 0.29	30.62 ± 0.24	29.95 ± 0.33	30.98 ± 0.23
Crude Fiber (%)	5.15 ± 0.06	4.85 ± 0.13	5.12 ± 0.05	5.24 ± 0.04
Energy (kj/g)	22.03 ± 0.44	24.30 ± 0.40	22.42 ± 0.27	23.99 ± 0.23

2.3. Grow out feeding trials

Feeding trials for grow-out were conducted in twelve 20 m^2 concrete earthen ponds at the Bunda Fish Farm over 126 days (18 weeks). The experiment followed a completely randomized design (CRD) with four dietary treatments, each replicated three times. The study used *O. shiranus* fingerlings with a mean weight of 15.02 ± 1.23 g which were obtained from the hatchery of Bunda Fish Farm. These fingerlings originated from broodstocks identified by experts during wild collection in Lake Malawi, following Konings (1990) guidelines, and were later placed in separate ponds for breeding to maintain proper taxonomic grouping. The fish seeds were acclimatized for 14 days, during which they were fed twice daily with the formulated feed used at the farm until near satiation, and all mortalities were recorded and removed. After acclimatization, the fingerlings were randomly assigned to experimental units and starved for 24 hours. Each pond was stocked with 60 fingerlings, and feeding was performed twice daily (9:00 AM and 4:00 PM) at a rate of 6% body weight. Feed quantities were adjusted biweekly based on the weight gain observed in 20 randomly sampled fish from each pond. Weight measurements were performed using a calibrated electronic balance (Yoshida model HL-200, accuracy ±0.1 g). At the end of the experiment, the surviving fish in each pond were counted to calculate their survival rate. Growth performance and feed utilization were evaluated using the formulae described in Chen et al. (2023) and Vasilaki et al. (2023), as outlined below:

a. $\textit{Mean weight gain}(g) = \textit{mean final weight}(g) - \textit{mean initial weight}(g)$ (1)

b. $\textit{Weight gain}(\%) = \dfrac{\textit{Final body weight}(g) - \textit{initial body weight}(g) \times 100}{\textit{initial body weight}(g)}$ (2)

c. $\text{Specific growth rate}(\text{SGR}) = \dfrac{\mathit{In}W_2 - \mathit{In}W_1}{T} \times 100$ (3)

d. $\text{Survival rate}(\%) = \dfrac{\text{No. of fish harvested} \times 100}{\text{No. of fish stocked}}$ (4)

e. $\text{Feed Intake}(\text{FE}) = \dfrac{\text{Dry diet(g)} \times 100}{\text{time intervall(initial weight(g)} + \text{final weight(g)} / 2)}$ (5)

f. $\textit{Apparent}\ \text{Feed conversion ratio}(\text{AFCR}) = \dfrac{\text{feed fed}}{\text{live weight gain;}}$ (6)

g. $\text{Hepatosomatic index}(\text{HIS})(\%) = \dfrac{\text{(weight of liver(g)}}{\text{total body weight}(\text{g})} \times 100$ (7)

2.4. Digestibility trial

Twelve 150-liter translucent circular tanks were used for the digestibility trial, with four experimental diets replicated three times. Each tank was stocked with 20 fish (52.86 ± 0.45g) obtained from a feeding trial. Fish were fed daily at 3% of their body weight. Water temperature was maintained between 26.5 °C and 29 °C using heaters, while aerators ensured that the dissolved oxygen levels remained between 5.50 and 7.00 mg/L. The pH was monitored and maintained within the range of 6.8 to 8.0. Chromic oxide analysis of both test diets and feces was performed using spectrophotometry. Chromic oxide was used as an inert marker to assess digestibility. The test and reference diets, along with fecal samples, were analyzed using spectrophotometry. Approximately 50–100 mg of each sample was digested in 5 ml of concentrated nitric acid in a Kjeldahl flask and heated for 20 minutes before cooling. Then, 3 ml of 70% perchloric acid was added, and heating continued until the solution changed from green to orange. The digest was diluted to 100 ml with pure water and analyzed at 350 nm using a spectrophotometer. Chromic oxide content was determined using Agbo's (2008) formula. Apparent digestibility of dry matter was then calculated following the method of

$$\textit{ADC for nutrients} = 100 * \left[1\left(\frac{F}{D}\right) * \left(\frac{D_i}{F_i}\right)\right] \quad (8)$$

where D = % nutrient of diet, F = % nutrient of feces, Di = % $Cr2O_3$ of diet, and Fi = % $Cr2O_3$ of feces.

2.5. Water quality monitoring

Key water quality parameters were measured to ensure optimal water quality conditions throughout the experiment. These parameters included dissolved oxygen, pH, temperature, phosphorus, turbidity, conductivity, and total ammonia nitrogen. Water quality parameters were recorded twice daily at 06:00 and 14:00 hour using an Aqua Read AP-2000 multi-probe water analyzer. For each of the 12 experimental ponds, triplicate readings were obtained for each parameter during each measurement session.

2.6. Statistical analyses

Data were entered into Microsoft Excel 2019 (. xls) files, and exported to IBM SPSS Version 20 for statistical analysis. Prior to performing statistical tests, the Shapiro-Wilk test was applied to assess the normality of the data, while Levene's test was used to evaluate the homogeneity of variances. Differences in means for different treatments that were normally distributed and with homogeneous variance were tested using one-way Analysis of Variance (ANOVA) at a significance level of 0.05 ($\alpha = 0.05$). Post hoc comparisons were conducted using Tukey's Honestly Significant Difference (HSD) test to identify significant differences among the treatment group means. Polynomial contrasts were applied to assess the linear, quadratic, and cubic effects of yellow mealworm replacement levels on fish growth performance and apparent digestibility. Results are presented as mean ± standard error (SE). This comprehensive approach ensured a robust and reliable statistical interpretation of the experimental data.

3. Results

3.1. Growth performance

The growth performance of *O. shiranus* across the four dietary treatments is shown in Figure 1 and Table 3. The results indicated no significant differences in the growth rates of *O. shiranus* fed the four diets ($p > 0.05$). The treatments had a final mean weight which ranged from 48.62 g to 52.86 g. Higher final mean weight of 52.86 g was observed in diet 4, followed by Diet 1 (51.47 g), Diet 2 (49.63 g), and Diet 3 (48.62 g). Similarly, weight gain was not significantly different among the treatments, with mean weight gains ranging from 33.60 g to 37.87 g. Diet 4 had a growth rate which was 0.11 higher than diet 3, 0.9% higher than diet 2, and 0.4% higher than diet 1. Similarly, no statistically significant differences ($p > 0.05$) were observed in the specific growth rates (SGR) across the yellow mealworm protein diets. The survival rates (%) of *O. shiranus* also did not differ significantly ($p > 0.05$) among the diets, ranging from 70.56 ± 8.22% in Diet 1 to 78.33 ± 1.67% in Diet 2. However, hepatosomatic indices (HSI) had a significant effect, though the effect size was small. The HIS ranged from from 0.355% to 0.436%. The HSI values showed both linear ($p < 0.05$) and quadratic ($p < 0.05$) trends. HIS values were higher in Diet 1, decreased at intermediate replacement levels (Diets 2 and 3), and increased at the highest level of replacement (Diet 4). The study revealed no statistically significant differences in the feed intake of *O. shiranus* across dietary treatments, with values ranging from 2.34 g to 2.62 g. Furthermore, all four feeding trials had apparent feed conversion ratio (AFCR) which was not statistically significant and varied between 2.62 in diet 4 and 2.93 in Diet 1.

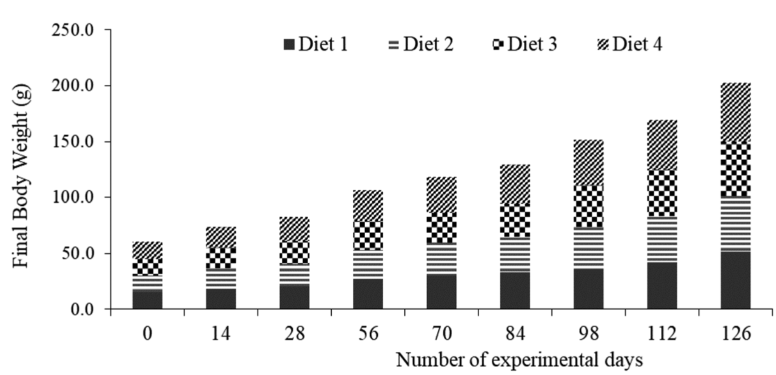

Figure 1. Growth performance in weight gain (g) of *Oreochromis shiranus* juveniles fed on the four different diets of Diet 1, Diet 2, Diet 3 and Diet 4 for 126 days.

Table 3. Growth parameters and feed utilization (mean ± SE) of *O. shiranus* fish fed at different replacement diets and their contrasts.

	Treatments				Contrast		
Growth parameters and indices	Diet 1 (%)	Diet 2 (25%)	Diet 3 (50%)	Diet 4 (75%)	Linear	Quadratic	Cubic
Initial Weight (g)	15.19 ± 0.24	15.06 ± 0.34	15.01 ± 0.55	14.95 ± 0.23	ns	ns	ns
Final Weight (g)	51.47 ± 1.97	49.63 ± 1.68	48.62 ± 1.95	52.86 ± 0.45	ns	ns	ns
Weight Gain (g)	36.28 ± 2.20	34.57 ± 1.87	33.60 ± 2.47	37.86 ± 0.29	ns	ns	ns
SGR (%-day)	3.18 ± 0.05	3.13 ± 0.05	3.11 ± 0.06	3.22 ± 0.01	ns	ns	ns
Survival rate (%)	70.56 ± 8.22	73.33 ± 7.26	78.33 ± 1.67	76.67 ± 7.64			
HSI (%)	0.428 ± 0.02[a]	0.378 ± 0.01[b]	0.355 ± 0.03[b]	0.436 ± 0.02[a]	*	*	ns
Feed intake (g/fish/day)	2.62 ± 0.157	2.58 ± 0.144	2.38 ± 0.476	2.34 ± 0.113	ns	ns	ns
AFCR (%)	2.93 ± 0.30	2.89 ± 0.28	2.67 ± 0.09	2.62 ± 0.22	ns	ns	ns

Note: Within the row, treatments with the same letter are not significantly different.
ns = no-significant.
*= significant.
AFCR = Feed conversion ratio.
SGR = Specific growth rate.
HSI = Hepatosomatic index.

Table 4. Proximate whole-body composition (mean ± SE) of *O. shiranus* at experiment termination of the experiment and their contrasts.

	Treatments					Contrast		
Parameters	Before experiment	Diet 1	Diet 2	Diet 3	Diet 4	Linear	Quadratic	Cubic
Moisture (%)	9.12 ± 0.58	7.70 ± 0.11	7.54 ± 0.016	7.32 ± 0.02	7.20 ± 0.06	ns	ns	ns
Ash (%)	12.18 ± 0.33	11.13 ± 0.59	11.16 ± 0.09	11.20 ± 0.73	11.32 ± 1.46	ns	ns	ns
Crude fat (%)	9.66 ± 0.08[b]	10.11 ± 0.02	10.07 ± 0.45	10.10 ± 0.07	10.23 ± 0.80	ns	ns	ns
Crude protein (%)	49.80 ± 2.10	51.04 ± 0.29	50.30 ± 0.39	50.35 ± 0.70	50.45 ± 0.74	Ns	ns	ns
Energy (kj/g)	19.24 ± 0.34	20.02 ± 0.87	20.93 ± 0.46	21.03 ± 0.54	20.80 ± 0.13	ns	ns	ns

Note: *Within the row, treatments with the same letter are not significantly different ($p < 0.05$) ns = no-significant,*
**= significant.*

3.2. Proximate composition analysis for fish

The total body composition of *O. shiranus* fed the experimental diets with different levels of yellow mealworm replacement is summarized in Table 4. The results revealed that replacing fishmeal with yellow mealworms had no significant effect on proximate composition of moisture, crude protein, ash content, crude fat and energy content ($p > 0.05$). When comparing proximate composition of fish before and after exposure to the diets, each of the four diet combinations had a similar proportion of moisture, ash, crude fat, crude protein and energy content.

3.3. Apparent nutrient digestibility

The apparent digestibility coefficients (ADC) of the tested feeds are presented in Table 5. The results showed that including yellow mealworm protein in the diet of *O. shiranus* up to 75% enhanced the digestibility of dry matter, ash, and crude fat, although the effect size was small for all factors. ADC values for dry matter and ash were higher for Diets 2, 3, and 4 than for Diet 1, following a significant linear trend ($p < 0.05$). These linear trends indicated that increasing the levels of yellow mealworm protein improved nutrient digestibility. In contrast, inclusion of yellow mealworm protein had no significant effect on the digestibility of crude protein or gross energy. This indicates that substituting fishmeal with yellow mealworm protein does not compromise digestibility or utilization of these key nutrients.

3.4. Water quality

The measured water quality parameters monitored during the experiment are presented in Table 6. The water quality parameters showed no significant differences ($p > 0.05$) in temperature, dissolved oxygen in

Table 5. Apparent digestibility coefficient (mean ± SE) for growth trial diets fed to *O. shiranus* and their contrasts.

	Treatments				Contrast		
Parameters	Diet 1	Diet 2	Diet 3	Diet 4	Linear	Quadratic	Cubic
Dry matter (%)	81.36 ± 0.13[a]	84.26 ± 0.01[b]	84.67 ± 0.21[b]	84.02 ± 0.03[b]	*	ns	ns
Ash (%)	88.10 ± 0.38[a]	92.06 ± 0.05[b]	92.66 ± 0.20[b]	92.20 ± 0.03[b]	*	ns	ns
Crude fat (%)	90.82 ± 0.07[a]	92.31 ± 0.00[b]	92.84 ± 0.10[b]	92.74 ± 0.07[b]	*	ns	ns
Crude Protein (%)	94.09 ± 0.06	93.79 ± 0.10	93.87 ± 0.08	94.54 ± 0.02	ns	ns	ns
Crude fibre (%)	90.51 ± 0.56	90.98 ± 0.24	92.74 ± 0.26	91.19 ± 0.37	ns	ns	ns
Gross energy (kj/g)	93.06 ± 0.04	93.72 ± 0.12	93.52 ± 0.09	94.29 ± 0.55	ns	ns	ns

Note: *Within the row, treatments with the same letter are not significantly different ($p < 0.05$); ns = no-significant.*
*= *significant; kJ/g = kilojoules per gram.*

Table 6. Water quality parameters measured (mean ± SE) during the growth study of *O. shiranus* and their contrast.

	Treatments				Contrast		
Parameters	Diet 1	Diet 2	Diet 3	Diet 4	Linear	Quadratic	Cubic
Temp (°C) AM	23.59 ± 0.06	23.56 ± 0.07	23.53 ± 0.06	23.68 ± 0.05	ns	ns	ns
Temp(°C) PM	25.65 ± 0.09	25.70 ± 0.07	25.86 ± 0.05	25.84 ± 0.07	ns	ns	ns
DO (mg/L) AM	3.51 ± 0.06[a]	3.00 ± 0.01[b]	3.00 ± 0.01[b]	3.16 ± 0.04[b]	*	ns	ns
DO (mg/L) PM	5.83 ± 0.04	6.15 ± 0.08	6.00 ± 0.00	6.00 ± 0.00	ns	ns	ns
pH Morning	7.05 ± 0.26	7.06 ± 0.03	7.26 ± 0.08	7.23 ± 0.08	Ns	Ns	ns
pH Afternoon	7.43 ± 0.02	7.43 ± 0.02	7.45 ± 0.02	7.45 ± 0.03	Ns	ns	ns
Ammonia (mg/L)	0.03 ± 0.00	0.03 ± 0.00	0.03 ± 0.00	0.03 ± 0.00	Ns	Ns	ns
Phosphorus (mg/L)	0.13 ± 0.01	0.12 ± 0.01	0.12 ± 0.01	0.13 ± 0.01	ns	ns	ns
Chlorophyll *a* mg/m^3	0.33 ± 0.17	0.44 ± 0.18	0.22 ± 0.15	0.56 ± 0.18	ns	ns	ns
Turbidity (NTU)	27.49 ± 0.22	27.31 ± 0.20	27.43 ± 0.20	27.54 ± 0.21	ns	ns	ns

Note: Within the row, treatments with the same letter are not significantly different ($p < 0.05$). ns = not significant,
*= significant. DO = Dissolved Oxygen.

the afternoon, pH, ammonia, phosphorus, chlorophyll *a*, and turbidity. Morning and afternoon temperatures ranged from 23.53–to 23.68 °C and 25.65–to 25.86 °C, respectively. Significant difference was observed on dissolved oxygen levels recorded in the morning. Diet one had higher dissolved oxygen of 3.51 mg/L compared to those with yellow mealworm inclusions. In the afternoon, dissolved was not significant different among four diet treatments. Minimum pH was recorded in the morning (7.05 ± 0.26) and higher pH was recorded in the afternoon (7.45 ± 0.03). The ammonia levels were consistent at ~0.03 mg/L across treatments. Chlorophyll *a* ranged from 0.22–0.56 mg/L, while phosphorus ranged from 0.12–0.13 mg/L. Turbidity values were between 27.31–27.49 NTU, with no significant differences among treatments ($p > 0.05$).

4. Discussion

The growth, feed utilization, and digestibility of *O. shiranus* fed dietary yellow mealworm larvae meal raised in earthen ponds have been evaluated, and to the best of our knowledge, this is the first attempt at juvenile *O. shiranus*. The present study revealed that there were no significant differences in final weight, weight gain, and specific growth rate (SGR) among different yellow mealworm replacement diets. This suggests that the yellow mealworm performs comparably to fish meal in terms of supporting the growth of *O. shiranus* juveniles due to their similar nutritional profile to fish meal, particularly in terms of protein and energy (Chen et al., 2023). This study demonstrated that yellow mealworm inclusion did not negatively affect growth rate, suggesting that fishmeal can be replaced with yellow mealworms at levels up to 75%. However, the optimal replacement level may vary depending on factors such as fish species, size, processing methods, and feed administration (Vasilaki et al., 2023). Furthermore, the use or replacement of fishmeal with yellow mealworms up to 75% might depend on understanding the effects of such inclusion on histological parameters of fish. Our findings partially agree with Belforti et al. (2015) who indicated that feeding rainbow trout up to 50% yellow mealworms had no effect on their final body weight. Similarly, Mazlum et al. (2021) reported a significant weight gain in crayfish fed a 50% yellow mealworm replacement diet. However, it contrasts with Anany et al. (2025) who reported higher final weight and SGR in *O. niloticus* fed fishmeal with *Saccharomyces cerevisiae* supplements, and greater weight gain with fishmeal alone. Similarly, Gasco et al. (2016) indicated that high levels of diet replacement (≥25–30%) may negatively affect fish performance owing to nutritional deficiencies. Additionally, Motte et al. (2019) found that replacing fishmeal with yellow mealworm from 25% to 75% resulted in significant differences in weight gain. These variations may be attributed to differences in the fish species, growth stage, feed formulation, insect biomass processing methods, and dietary administration period (Maulu et al., 2022; Vasilaki et al., 2023).

Furthermore, the current study demonstrated that mealworm-supplemented diets enhanced feed utilization in *O. shiranus* juveniles, with no effect on feed consumption. This could be because the efficiency at which the fish used the feed for growth or other physiological functions was maintained across all levels of yellow mealworm replacement in the diet. It also suggests that inclusion of yellow mealworm did not affect feed consumption. This is in tandem with Choi et al. (2018) who found no effect of the yellow mealworm on feed intake in white pacific shrimp. In contrast, Belforti et al. (2015) found that replacing fish meal with 25 or 50% yellow mealworm in the diet significantly altered feed intake in rainbow trout.

Furthermore, the lack of a significant effect of mealworms on the apparent feed conversion ratio (AFCR) suggests that *O. shiranus* juveniles are capable of efficiently converting diets with yellow mealworm replacement for fish meal. This finding aligns with that of Gasco et al. (2016), who reported no negative effect on AFCR when fishmeal was replaced with mealworm larval meal in European sea bass diets. In contrast, Motte et al. (2019) yellow mealworm replacement levels affected the AFCR of the Pacific white shrimp (*L. vannamei*). This discrepancy may be attributed to differences in rearing conditions and species (Maulu et al., 2022; Vasilaki et al., 2023). For instance, fish in the present study were raised in ponds, whereas those in another study were reared in fiberglass tanks, which could have influenced the determination of AFCR.

Furthermore, higher hepatosomatic index (HSI) values in *O. shiranus* were recorded at 100% fishmeal and 75% yellow mealworm inclusion. A higher HSI typically indicates that a fish is well-nourished with good access to food, as a larger liver suggests greater energy reserves (Prakash, 2022; Sureshkumar & Kurup, 1999). However, it can also reflect a response to pollution or environmental stress (Prakash, 2022). Therefore, the diets with 100% fishmeal and 75% yellow mealworm inclusion may have improved the nutritional well-being of the fish. Sureshkumar and Kurup (1999) reported that higher HSI and protein levels were associated with improved somatic growth in *Macrobrachium rosenbergii*, serving as key indicators of better nutritional status and energy reserves that support faster growth. However, HSI values in the present study were lower than those reported by Belforti et al. (2015) in rainbow trout and Sankian et al. (2018) in *Siniperca scherzeri* juveniles when yellow mealworm was included in the diet. This discrepancy could be attributed to differences in species type and size, which can influence liver size.

For the apparent digestibility coefficient (ADC), it was noted that replacing fishmeal with yellow mealworm significantly enhanced protein digestibility, especially in Diet 4. This suggests that yellow mealworms are digestible by *O. shiranus* and do not have any interactions affecting digestibility (Anany et al., 2025; Glencross et al., 2007). Therefore, it can be suggested that yellow mealworm replacement improves the capacity of *O. shiranus* to metabolize nutrients. This finding is in line with Gasco et al. (2016) findings that replacing fish meal with yellow mealworm increased the ADC of gilthead sea bream (*Dicentrarchus labrax*) compared to diets containing fishmeal.

Regarding the effect of yellow mealworm on the whole-body composition of *O. shiranus*, it was revealed that all proximate parameters were similar across different diets. These results suggest that nutrient metabolism in *O. shiranus* was not negatively affected, as reflected in whole-body composition. This finding aligns with that of Sankian et al. (2018), who observed similar results in the fillet composition of mandarin fish (*Siniperca scherzeri*) fed with yellow mealworms. However, the literature shows conflicting findings regarding the effect of insect meal replacement on whole-body composition. Some studies Belforti et al. (2015) and Gasco et al. (2016) reported significant effects, whereas others Devic et al. (2018); Iaconisi et al. (2017) and Sánchez-Muros et al. (2016) found no significant effects. These discrepancies may be attributed to varying replacement levels or differences in the species used for insect meal replacement (Sankian et al., 2018).

In this study, critical water parameters remained within recommended concentrations across all four treatments. This suggests that yellow mealworm inclusion did not lead to substantial changes in key water quality parameters. This indicate that the fish effectively consumed and digested the yellow mealworms, with little to no effect of residual waste on water quality. Additionally, the nutritional composition of yellow mealworms may not produce excessive waste products that could negatively affect water quality. Similar results regarding the lack of effect of mealworm inclusion on water quality were also reported by Sankian et al. (2018).

5. Conclusion and recommendations

The study found that replacing fishmeal with yellow mealworms in the diets of *O. shiranus* did not affect growth parameters or feed utilization metrics, such as feed intake and the apparent feed conversion ratio. Although the hepatosomatic indices were influenced by yellow mealworm protein-based diets, the values remained within the recommended ranges. The high apparent digestibility coefficients (ADC) of all test diets, exceeding 50%, indicated effective utilization for tissue synthesis and metabolic activity. These findings suggest that mealworm larva meal can serve as an alternative protein source for fish nutrition, comparable to fishmeal. Hence, yellow mealworms can be substituted for up to 75% of fishmeal in the diet of *O. shiranus* without adversely affecting fish growth, feed utilization, or digestibility. However, the present study did not consider histological effects of replacing fish meal with yellow mealworm, hence, future studies should consider unravelling this critical effect on *O.shiranus* especially at recommended 75% replacement level. Additionally, it will be vital to explore the feasibility of a complete (100%) replacement of fishmeal with yellow mealworms by assessing its effects on *O.shiranus* growth performance, nutrient assimilation, and fish health. Future studies should consider investigating economic viability of yellow mealworm compared to fishmeal for both small-scale and commercial fish farmers to ascertain and foster its scalability for aquaculture sector.

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Ethical approval

Ethical review and approval were obtained from the LUANAR Research Ethics Committee under protocol number LUANAR-REC-REVIEW-2023-0007.

Author's contribution

CRediT: **Thokozire Gwaza**: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Visualization, Writing – original draft; **Jeremiah Kang'ombe**: Formal analysis, Supervision, Validation, Writing – review & editing; **Daniel Sikawa**: Investigation, Supervision, Writing – review & editing; **Kingdom Simfukwe**: Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing; **Patrick Singoyi**: Formal analysis, Investigation, Visualization, Writing – review & editing; **Joseph Mphande**: Formal analysis, Investigation, Methodology, Writing – review & editing; **Emmanuel Kaunda**: Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing. All authors have read and agreed to the final version of the manuscript submitted.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ARRIVE guidelines compliance statement

To ensure ethical and transparent reporting of animal research, Animal Research: Reporting of In Vivo Experiments (ARRIVE) Guidelines were followed in conducting the study. The experiment was conducted to minimize animal suffering and it was approved by the relevant ethical body [LUANAR Research Ethics Committee] under protocol number LUANAR-REC-REVIEW-2023-0007 in Malawi. The completed ARRIVE checklist has been attached as supplementary document with all experiment details reported.

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Data availability statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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