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Original Research Article

Effects of fish meal replacement on production and economics of tilapia monoculture systems in ponds

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ABSTRACT

The effects of partially replacing fish meal with locally available mustard oil cake (MOC) were evaluated on production, feed utilization, greenhouse gas (GHG) emissions, and economic returns of monosex tilapia (*Oreochromis niloticus*) cultured in nine farmer-managed ponds at Harian of Paba Upazila, Rajshahi, Bangladesh. The study addressed rising fish meal cost, import dependency and the need for affordable, locally sourced, climate-smart feed alternatives. Three isonitrogenous diets (28% crude protein) were tested in a randomized complete block design with three replicates: T_1 (30% fish meal, 25% MOC; 0% replacement), T_2 (25% fish meal, 30% MOC; 16.7% replacement), and T_3 (20% fish meal, 35% MOC; 33.3% replacement). Fish were stocked at 50,000 ha^{-1} across treatments. Fish meal replacement significantly ($p<0.05$) affected water quality, growth, feed utilization, yield, GHG emissions, and profitability. Methane emissions declined from 0.000027 $\pm$ 0.0000003 Gg year^{-1} in T_1 to 0.000024 $\pm$ 0.0000005 Gg year^{-1} in T_3, while N_2O-N emissions decreased from 0.0163 $\pm$ 0.00015 to 0.0136 $\pm$ 0.00012 Gg year^{-1}. The highest final weight (246.18 $\pm$ 3.93 g), weight gain (224.90 $\pm$ 3.69 g), and survival (89.05 $\pm$ 2.89%) attained in T_1, followed by T_2, whereas T_3 exhibited lowest FCR (1.68 $\pm$ 0.05). Although T_1 produced highest gross return (1,315,452 $\pm$ 53,736), T_2 generated greatest net profit (BDT 579,678.33/$ 4734.90 $\pm$ 100,210 ha^{-1}) and cost–benefit ratio (0.89 $\pm$ 0.15). Thus, 16.7% fish meal replacement with MOC elevates production, profitability, and lower GHG emissions for sustainable tilapia farming in Bangladesh.

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INTRODUCTION

Aquaculture is the world's fastest-growing food production sector and is vital for food security, livelihoods, and economic growth. As demand for aquatic foods continues to rise, the challenge is not only to increase production but also to improve the economic, climate change and environmental sustainability of aquaculture systems. According to FAO (2024), the continued growth of aquaculture is essential to meeting increasing demand for aquatic foods and supporting food security. In Bangladesh, the fisheries sector contributes 2.53% to national GDP, 22.26% to agricultural GDP, and 0.91% to foreign exchange earnings, while supporting the livelihoods of over 20 million people, including 1.4 million women (DoF, 2024). Bangladesh ranks fifth globally in aquaculture production, and fish supplies nearly 60% of the country's daily animal protein intake (FAO, 2024). Among cultured species, tilapia (*Oreochromis niloticus*) has become an important commercial species because of its rapid growth, adaptability to diverse environmental conditions, high productivity, and capacity to utilize formulated diets. It is one of the most extensively farmed species in Bangladesh and has demonstrated strong performance across diverse freshwater systems (Nasrin *et al.*, 2021). However, intensive tilapia farming relies heavily on formulated feed, which accounts for 40–70% of production costs and significantly influences environmental sustainability (Afram *et al.*, 2021 and Rahman *et al.*, 2023). Fish meal remains the principal protein source, yet increasing costs and limited supply have intensified the search for plant-based alternatives such as soybean meal and mustard oil cake (Pervin *et al.*, 2020).

Consequently, the increasing cost and uncertain availability of high-quality feed ingredients, particularly fish meal, remain important constraints to profitable tilapia production.

Fish meal is known as widely valued aqua-feed protein source because of its favorable amino acid profile and high digestibility. However, its high price, limited supply, and dependence on marine resources have stimulated efforts to identify cost-effective and sustainable alternatives. Recent studies have demonstrated the potential for partial replacement of fish meal with locally available plant-based protein sources in tilapia diets, provided that nutritional requirements are adequately maintained (Hua, 2021; Abdel-Latif *et al.*, 2022; Boonmee *et al.*, 2024). In Bangladesh, locally available agricultural by-products may offer particular advantages by reducing feed costs and dependence on externally sourced ingredients. Mustard oil cake (MOC), a by-product of mustard oil extraction, is widely available and has potential as a relatively low-cost protein ingredient for aqua-feeds. Its utilization could strengthen the linkage between agriculture and aquaculture while promoting more resource-efficient, economically viable and locally adapted production systems. The use of local agricultural by-products further supports circular economy principles, adds value to waste streams, and stimulates rural livelihoods through demand for domestic feed resources.

Aquaculture sustainability extends beyond farm profitability and economic returns and also can contribute to greenhouse gas (GHG) emissions through feed production, nutrient inputs, accumulation of organic matter, and overall management systems. Freshwater aquaculture ponds may emit substantial quantities of methane (CH_4) and nitrous oxide (N_2O), with emissions influenced by feeding intensity, nutrient loading, sediment conditions, and farm management practices (MacLeod *et al.*, 2020; Rosentreter *et al.*, 2021; Zhang *et al.*, 2024). Therefore, the selection of feed ingredients and feeding management systems have implications not only for fish production costs but also for the climate change and environmental performance of aquaculture systems. So far, considerable research has examined plant-based alternatives to fish meal, but most previous studies have primarily focused on growth performance and its feed utilization. Limited information is available on the integrated effects of fish meal replacement on production and economic performance under farmer-managed pond conditions, particularly in Bangladesh. Specifically, there is insufficient evidence regarding the optimum level of replacing fish meal with locally available and adaptable / affordable MOC in tilapia monoculture systems in Bangladesh. Further, very few studies have simultaneously examined the potential business acumen between fish growth, feed efficiency, production, economic returns, and environmental and climate change aspects under practical pond farming conditions.

Therefore, the uniqueness of the present study, lies in its integrated assessment of graded fish meal replacement with locally available and adaptable MOC in farmer-managed tilapia ponds, adhering with the biological performance and with farm-level economic outcomes and climate-smart aspects. The present study is aimed to provide practical evidence on whether reducing fish meal inclusion can improve the economic efficiency of tilapia farming without substantially compromising production performance and climate change issues. Against this background, the present study evaluates the effects of partial replacement of fish meal with MOC on water quality, greenhouse gas emissions, growth performance, yield, and economic returns in tilapia monoculture systems in ponds. The study aimed to identify an appropriate level of fish meal replacement that could provide a practical balance between fish production, feed efficiency, farm profitability, climate change and environmental sustainability, thereby contributing to more cost-effective and climate-responsive tilapia monoculture systems in Bangladesh.

MATERIALS AND METHODS

Study area and experimental design

The experiment was conducted over six months, from July to December 2025, in farmer-managed ponds (mean area of 0.04 $\pm$ 0.01 ha and depth of 1.51 $\pm$ 0.19 m) located at Harian of Paba Upazila under Rajshahi District, Bangladesh. A Randomized Complete Block Design (RCBD) was used to evaluate the effects of graded replacement of fish meal with mustard oil cake (MOC) in the diets of *Oreochromis niloticus*. Three replacements of fish meal were tested under three different treatments: T_1 (30% fish meal and 25% MOC; 0% replacement), T_2 (25% fish meal and 30% MOC; 16.7% replacement), and T_3 (20% fish meal and 35% MOC; 33.3% replacement). The remaining ingredients were adjusted to achieve a total diet composition of 100% while maintaining the target crude protein level of 28%. Each treatment was replicated thrice, with stocking density 50,000 fishes/ha), initial fish stocking weight (21.62 $\pm$ 1.40g), and culture duration kept constant across treatments. The 16.7% and 33.3% replacement values are calculated based on the reduction in fish meal relative to the fish meal level in the control diet (T_1), not on the total feed composition. The general formula is:

Treatment 1 : Fish meal replacement (%) = 30-30 / 30 x 100 = 0%

Treatment 2 : Fish meal replacement (%) = 30-25 / 30 x 100 = 5/30 x 100 = 16.67%

Treatment 3 : Fish meal replacement (%) = 30-20 / 30 x 100 = 10/30 x 100 = 33.33%

Pond management

Prior to stocking, aquatic weeds were manually removed from all experimental ponds, and predatory as well as unwanted fish species were eliminated through repeated netting. The ponds were subsequently limed at a rate of 250 kg/ha. Seven days after liming, inorganic fertilizers were applied at 25 kg/ha urea and 15 kg/ha TSP to enhance natural pond productivity. Hatchery produced tilapia (*Oreochromis niloticus*) fingerlings were stocked three days after basal fertilization during the morning hours. Fish were fed according to biomass, starting at 5% of body weight during the first month and gradually reduced to 4%, 3%, and 2% over the course of the trial. Feed was administered twice daily, with equal portions provided in the morning (8:00–9:00 A.M.) and afternoon (5:00–6:00 P.M.).

Water quality management

Key physico-chemical parameters, including temperature, transparency, dissolved oxygen (DO), pH, carbon dioxide (CO_2), ammonia-nitrogen (NH_3-N), total alkalinity, and total dissolved solids (TDS), were monitored monthly between 8:30 and 10:30 A.M. to assess pond water quality. Water temperature was measured at a depth of 20–30 cm below the surface using a Celsius thermometer, while transparency was determined using a Secchi disk and recorded as Secchi depth (cm). Measurements for temperature and transparency were taken three times, and mean values were calculated. The pH, DO, and TDS were measured using a multiparameter meter

(HQ 40D; HACH, USA). Concentrations of CO_2, NH_3-N, and total alkalinity were determined using a water quality testing kit (HACH FF-2, USA). All chemical parameters were expressed in mg/L. Standardized procedures and repeated measurements ensured accuracy and reliability of the collected water quality data throughout the experimental period.

Quantitative analysis of CH_4 and N_2O

CH_4 emission was determined after Lesschen *et al.* (2011) as follows:

$$\mathrm{CH_4\ emission\ (Gg\ CH_4\ yr^{-1})} = \sum (EF \times T \times A) \times 10^{-6} \quad (1)$$

Here, EF stands for methane emission factor= 0.351 kg CH_4 $ha^{-1}day^{-1}$, T is cultivation period (day) = 180 days, A stands for harvested area = 0.04 hectare, and the factor 10^{-6} converts the estimated methane emissions from kilograms (kg) to gigagrams (Gg).

N_2O-N emission was determined after Hu *et al.* (2012) as follows:

$$\mathrm{N_2O{-}N\ emission\ (Gg\ N_2O{-}N\ yr^{-1})} = \sum (EF \times P) \times 10^{-3} \quad (2)$$

Where, EF is the N_2O–N emission factor (0.00169 kg N_2O–N metric ton^{-1} production yr^{-1}), P is the total annual fish production (metric tons), and 10^{-3} converts emissions from kilograms (kg) to metric tons (or apply the appropriate conversion factor according to the reporting unit).

All estimated greenhouse gas (GHG) emissions were subsequently converted into carbon dioxide equivalents (CO_2e) using their respective 100-year Global Warming Potential (GWP100) values. The GWP factors applied were 28 for CH_4 and 265 for N_2O, relative to CO_2, following Myhre *et al.*, (2013). Total global warming potential was calculated as:

$$\mathrm{Total\ GWP\ (CO_2\text{-}e)} = (28 \times CH_4) + (265 \times N_2O) \quad (3)$$

Where, CH_4 and N_2O represent the estimated emissions from the culture system. Note: N_2O–N was converted to N_2O by multiplying by 44/28, followed by application of the GWP_{100} factor of 265.

Fish growth and yield

At 30-day intervals, 10% of the stocked fish from each experimental pond were randomly sampled using a cast net to monitor growth performance. The collected data were used to evaluate growth parameters of the stocked fish under different treatments using the following formulas.

Initial weight (g): weight of fish at stock.

Final weight (g): weight of fish at harvest.

Weight gain (g): Mean final weight (g) - Mean initial weight (g).

Specific growth rate: SGR (%, bwd^{-1}) = Ln w_2-Lnw_i / T x 100

Where, W_2 = final weight of fish; W_1 = Initial weight of fish, and T= Culture period in days.

Survival rate (%) = number of fish harvested / Number of fish stocked x 100

Yield (kg ha^{-1}) = Fish biomass at harvest (kg) – Fish biomass at stocking (kg) / Pond area (ha)

FCR = Total Fed Given (kg) / Total Biomass Gain (kg)

Economics of the tilapia monoculture

A simple cost–benefit analysis was conducted to evaluate the economic performance of tilapia farming under different treatments. Both fixed and variable costs were recorded to estimate the total cost (BDT/ha/180 days; 1 USD = 122 BDT in December 2025). Total return, based on the market value of harvested fish, was expressed as BDT/ha/180 days (BDT 120 per kg). Net benefit was calculated by subtracting total cost from total return and presented as BDT/ha/180 days. The cost–benefit ratio (CBR) was computed as follows:

CBR = Net benefit = Total production cost

Total Return (DBT ha^{-1} per 6 months) = Yield (kg ha^{-1} per 6 months) x Fish Selling Price (DBT kg^{-1})

Statistical analysis

The experimental data were statistically analyzed using one-way analysis of variance (ANOVA) in SPSS (Version 21). When significant differences were detected, mean comparisons were performed using Duncan's Multiple Range Test (DMRT) at a 5% level of significance (*$p<0.05$*).

RESULTS AND DISCUSSION

Water quality

During the study, water quality parameters varied among the treatments which indicates that partial replacement of fish meal with MOC influenced some of the aspects of the pond environment (Table 1). Water temperature remained stable across treatments (30.72 ± 0.73 to 31.34 ± 1.37°C) with no significant differences (*$p>0.05$*), indicating suitable thermal conditions for tilapia culture caused all of the ponds were located in the same area and monitored during the same period. The current study showed the consistent and recommended range of 25–32°C for warm-water aquaculture species and supported by previous findings (Abd El-Hack *et al.*, 2022; Rahman *et al.*, 2023; FAO, 2024; Boonmee *et al.*, 2024). Transparency increased significantly (p < 0.05) from 31.11 ± 2.01 cm in T_1 to 36.44 ± 2.52 cm in T_3, possibly reflecting lower suspended organic matter and feed residues with higher MOC inclusion, though the current results within productive ranges reported by Ferdoushi *et al.*, (2021) and Khalil *et al.*, (2022). However, transparency in earthen ponds is also influenced by phytoplankton, suspended sediments, and other environmental factors. Similarly, dissolve oxygen (DO) increased significantly from 4.71 ± 0.41 mg/L in T_1 to 5.74 ± 0.39 mg/L in T_3 (p < 0.05). The higher DO may be associated with lower oxygen demand resulting from reduced ammonia and dissolved solids, although this mechanism requires further investigation. These values were comparable with recent tilapia studies reporting favorable water conditions under adequate DO levels (Abd El-Hack *et al.*, 2022; Maundu *et al.*, 2024). Carbon dioxide (4.97 ± 0.57 to 5.40 ± 0.88 mg/L) and pH (6.03 ± 0.69 to 6.31 ± 0.67) showed no significant differences (p > 0.05), indicating that MOC replacement did not substantially affect the acid–base balance of pond water. Similar findings have emphasized the importance of stable pH and adequate DO for maintaining suitable conditions for tilapia culture (Abd El-Hack *et al.*, 2022; Maundu *et al.*, 2024). Total alkalinity decreased significantly from 91.44 ± 6.68 mg/L in T_1 to 85.23 ± 6.29 mg/L in T_3, possibly due to differences in nutrient cycling, microbial activity, and nitrogen transformation, though values remained within the suitable range for fish culture (El-Sayed, 2020; FAO, 2024). Ammonia-nitrogen (NH_3-N) decreased significantly (p < 0.05) from 0.36 ± 0.09 mg/L in T_1 to 0.18 ±

0.03 mg/L in T_3, suggesting reduced nitrogen accumulation or differences in nitrogen utilization and transformation. The concurrent improvement in DO may also have supported favorable nitrogen cycling (Abd El-Hack *et al.*, 2022; Maundu *et al.*, 2024). Likewise, total dissolve solid (TDS) declined significantly from 564.44 ± 20.41 mg/L in T_1 to 523.07 ± 12.44 mg/L in T_3, possibly reflecting lower concentrations of dissolved organic and inorganic materials. The current findings also supported by El-Sayed (2020) and FAO (2024).

Table 1. Mean water quality in ponds under different treatments of protein levels.

Water quality	Treatments		
	T_1	T_2	T_3
Temperature (°C)	31.34 ± 1.37^a	31.04 ± 0.85^a	30.72 ± 0.73^a
Transparency (cm)	31.11 ± 2.01^a	33.78 ± 1.52^b	$36.44 \pm 2.^{52c}$
DO (mg/L)	4.71 ± 0.41^a	5.06 ± 0.49^b	5.74 ± 0.39^c
CO_2 (mg/L)	5.40 ± 0.88^a	4.97 ± 0.57^a	5.25 ± 0.57^a
pH	6.03 ± 0.69^a	6.17 ± 0.68^a	6.31 ± 0.67^a
Alkalinity (mg/L)	91.44 ± 6.68^b	87.44 ± 5.56^c	85.23 ± 6.29^a
NH_3-N (mg/L)	0.36 ± 0.09^c	0.22 ± 0.03^b	0.18 ± 0.03^a
TDS (mg/L)	564.44 ± 20.41^c	537.62 ± 19.21^b	523.07 ± 12.44^a

Values sharing the same superscript letter(s) within a row are not significantly different at the 5% probability level (p > 0.05).

Overall, higher MOC inclusion did not adversely affect pond water quality and was associated with higher transparency and DO and lower NH_3-N and TDS. Rahman *et al.*, (2023) similarly reported the potential for replacing fish meal with locally available plant protein sources in Nile tilapia diets, although higher replacement levels may reduce growth performance. Therefore, the optimum replacement level should balance water quality, growth, feed utilization, production, and economic returns, rather than maximizing fish meal replacement alone.

Greenhouse gas emission

The present study showed that increasing replacement of fish meal with MOC significantly reduced pond GHG emissions (Table 2 and Figure 1). Methane (CH_4) emissions declined from 0.000027 ± 0.0000003 Gg year^{-1} in T_1 to 0.000024 ± 0.0000005 Gg year^{-1} in T_3, while N_2O-N emissions decreased from 0.0163 ± 0.00015 to 0.0136 ± 0.00012 Gg year^{-1} ($p < 0.05$). Consequently, total GHG emissions during the six-month culture period decreased from 4.38 ± 0.055 kg CO_2e ha^{-1} in T_1 to 3.60 ± 0.034 kg CO_2e ha^{-1} in T_3, equivalent to annual emissions of 8.75 ± 0.110 and 7.19 ± 0.067 kg CO_2e ha^{-1} year^{-1}, respectively. These results are consistent with previous studies indicating that poor feed management and deteriorated water quality can substantially increase GHG emissions from aquaculture ponds (MacLeod *et al.*, 2020). Similarly, Islam *et al.*, (2020) emphasized that emissions from the aquaculture sector can be mitigated through improved feed management, enhanced feed conversion efficiency, and reduction of pond-derived nitrous oxide (N_2O). Thus, the highest level of fish meal replacement produced an approximately 18% reduction in annualized total GHG emissions compared with T_1. More recently, a Bangladesh-based study by Luba *et al.*, (2026) reported that feed load and composition were closely associated with GHG emissions from freshwater aquaculture systems. More intensive systems using higher feed inputs showed substantially greater CH_4, N_2O, and CO_2 emissions than tilapia and carp systems. This recent evidence provides particularly relevant support for the present results, as the lower NH_3-N, TDS, and higher DO observed with greater MOC inclusion may indicate more favorable pond conditions for limiting GHG-generating processes. The present findings therefore suggest that dietary reformulation using locally available plant protein can contribute to lowering the environmental footprint of pond-based tilapia culture. Nevertheless, lower emissions alone should not determine the optimum replacement level, because T_3 also needs to be evaluated against its effects on growth, yield, feed efficiency, and profitability.

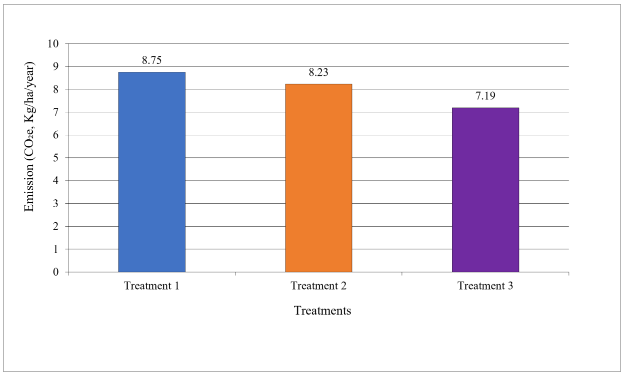

Figure 1. *Total greenhouse gas emissions (kg CO_2e ha^{-1} year^{-1}) under different dietary treatments.*

Table 2. Annual greenhouse gases (GHGs) emission of tilapia farming in ponds under different treatments.

GHGs (Gg/year)	Treatment		
	T1	T2	T3
CH_4	0.000027 ± 0.0000003^c	0.000026 ± 0.0000005^b	0.000024 ± 0.0000005^a
N_2O-N	0.0163 ± 0.00015^c	0.0156 ± 0.00026^b	0.0136 ± 0.00012^a
Total emission (CO_2e, Kg/ha/6 month)	4.38 ± 0.055^c	4.12 ± 0.035^b	3.60 ± 0.034^a
Total emission (CO_2e, Kg/ha/year)	8.75 ± 0.110^c	8.23 ± 0.070^b	7.19 ± 0.067^a

Values sharing the same superscript letter(s) within a row are not significantly different at the 5% probability level (p > 0.05).

Overall, the results indicate that fish meal replacement has the potential to reduce pond-level GHG emissions, but the most sustainable feeding strategy should balance environmental gains with biological performance and economic returns.

Fish growth and yield

Monthly variation in weight gain and Specific Growth Rate (SGR)

Monthly variation in weight gain and specific growth rate (SGR) showed that seasonal and environmental factors influenced tilapia growth more strongly than dietary treatments (Figures 2 and 3). Despite differences in fish meal and MOC levels, all treatments followed a similar growth pattern, which is indicating that pond environmental conditions were the main drivers of monthly growth performance. During the first month, relatively high weight gain and SGR were recorded in all treatments. T_1 showed the highest weight gain (40.00 $\pm$ 0.00 g) and SGR (0.59 $\pm$ 0.02% body weight day^{-1}), but the relatively small differences among treatments, suggesting that favorable environmental conditions promoted growth across diets. Warm temperatures (around 28–30°C) enhance feed intake, metabolism, and growth in tilapia (Boonmee *et al.*, 2024). Growth remained relatively stable during the second to fourth months, and no significant differences (p > 0.05) were observed among treatments for weight gain or SGR. This result suggests that, under relatively favorable and stable pond conditions, the partial replacement of fish meal with MOC did not substantially impair growth. This finding is consistent with recent research showing that plant-based protein ingredients can partially replace fish meal without major reductions in tilapia growth when diets are nutritionally balanced (Rahman *et al.*, 2023). Similarly, Sallam *et al.*, (2021) found that moderate replacement of fish meal with rapeseed meal could maintain or even improve growth and SGR in *O. niloticus*, although excessive replacement may negatively affect performance. The lack of significant differences suggests that the isonitrogenous diets provided sufficient nutrients and that MOC levels were within a tolerable range. However, differences in digestibility and nutrient availability may become more evident under environmental stress, particularly as temperature affects nutrient utilization in tilapia (Dey *et al.*, 2024). A clear decline in growth was observed during the fifth and sixth months across all treatments. During the fifth month, weight gain declined to 33.63 $\pm$ 2.72 g, 31.13 $\pm$ 1.68 g, and 26.18 $\pm$ 3.81 g in T_1, T_2, and T_3, respectively, and SGR showed a similar declining pattern. Although T_1 and T_2 outperformed T_3 during the later months, growth declined across all treatments, indicating that seasonal changes were the main driver. Cooler winter temperatures likely reduced metabolism, feed intake, digestion, and nutrient utilization. This interpretation is strongly supported by recent studies of Boonmee *et al.*, (2024), Suárez-Puerto *et al.*, (2021) and Siddique *et al.*, (2025). Thus, the reduction observed in the fifth and sixth months is unlikely to be explained by dietary treatment alone and more reasonably reflects the combined effects of seasonal cooling and associated changes in pond environmental conditions. The lower growth of T_3 in the final months suggests that dietary effects became more pronounced under environmental stress. It's higher MOC and lower fish meal levels may have reduced nutrient digestibility, especially at lower temperatures (Dey *et al.*, 2024).

Overall, seasonal variation was the main driver of changes in weight gain and SGR, while dietary effects were secondary. Growth was higher during favorable months and declined as conditions deteriorated. Monthly weight gain (23.30 $\pm$ 0.35–41.55 $\pm$ 0.42 g) and SGR (1.37 $\pm$ 0.00–2.80 $\pm$ 0.03% day^{-1}) were comparable with reported tilapia ranges, which vary with diet and culture conditions (Rapatsa & Moyo, 2022; Rahman *et al.*, 2023). These findings suggest that T_2 provided a better balance between fish meal replacement and growth stability, while the higher MOC level in T_3 may be less suitable under seasonal stress.

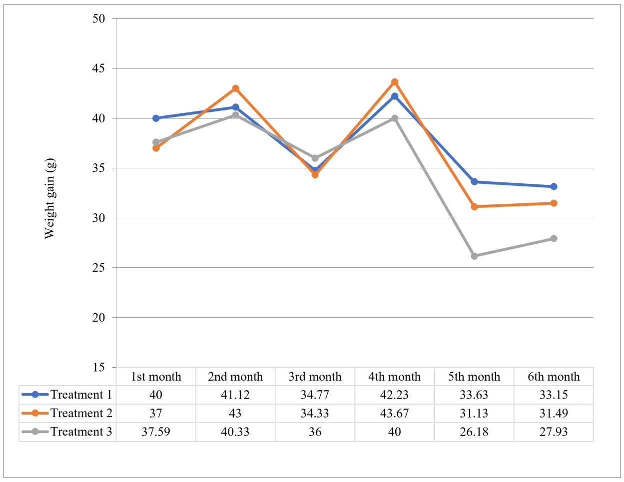

Figure 2. *Monthly variation in the weight gain (g) of tilapia under different dietary treatments.*

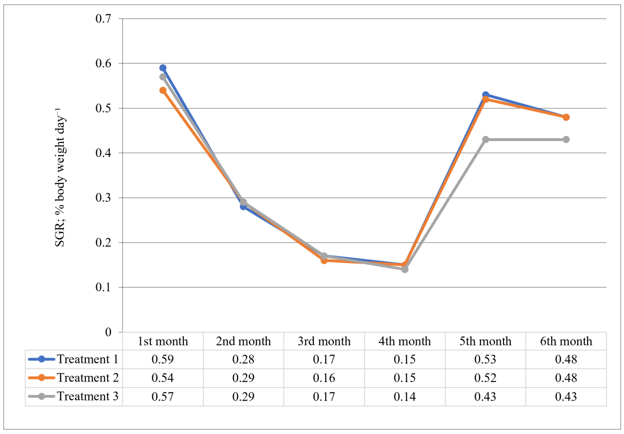

Figure 3. *Monthly changes in the specific growth rate (SGR; % body weight day^{-1}) of tilapia across different dietary treatments.*

Growth performance and yield of tilapia

The results demonstrated that partial replacement of fish meal significantly affected the growth, survival, and yield of tilapia (Table 3). The absence of significant differences in initial weight confirmed uniform stocking, while the significantly higher final weight, weight gain, and SGR in T_1 and T_2 compared with T_3 indicate that moderate fish meal replacement was well tolerated, but the higher replacement level in T_3 adversely affected performance. Fish in T_1 attained the highest final weight (246.18 $\pm$ 3.93 g) and weight gain (224.90 $\pm$ 3.69 g), followed closely by T_2 (242.95 $\pm$ 9.63 g and 220.62 $\pm$ 9.30 g, respectively), with both treatments significantly outperforming T_3. This suggests that replacing fish meal with MOC up to a moderate level maintained adequate nutrient supply, whereas the higher inclusion level in T_3 may have reduced feed palatability, protein digestibility, or amino acid availability. Plant protein sources can also contain higher fiber and anti-nutritional factors, which may reduce nutrient utilization when included at excessive levels. Recent studies similarly showed that the response of tilapia to fish meal replacement depends strongly on the replacement level and nutritional quality of the alternative protein source (Magbanua & Ragaza, 2024). The present findings closely agree with a recent 180-day pond study by Maundu *et al.*, (2024), who found that Nile tilapia fed diets with low plant-protein replacement showed growth and survival comparable to the control, whereas growth performance and protein digestibility declined significantly as replacement increased. Similarly, a recent study using rice polish and mustard oil cake reported a gradual decline in weight gain as fish meal was reduced and plant ingredients increased, although SGR differences were not statistically significant (Rahman *et al.*, 2023). These findings strongly support the present result, particularly the lower final weight and weight gain in T_3.

Table 3. Variation in mean growth performance and yield among different treatments in experimental ponds.

Parameter	Treatments		
	T_1	T_2	T_3
Initial weight (g)	21.29 ± 0.95^a	22.33 ± 2.29^a	21.23 ± 0.97^a
Final weight (g)	246.18 ± 3.93^a	242.95 ± 9.63^a	229.26 ± 4.05^b
Weight gain (g)	224.90 ± 3.69^a	220.62 ± 9.30^a	208.04 ± 3.94^b
SGR (%, bwd^{-1})	1.15 ± 0.01^a	1.13 ± 0.02^a	1.09 ± 0.01^b
Survival rate (%)	89.05 ± 2.89^a	84.25 ± 4.19^{ab}	81.10 ± 3.73^b
Yield (kg/ha/6 months)	$10,962.1 \pm 447.8^a$	$10,232.5 \pm 842.6^a$	$9,297.5 \pm 514.3^b$
Yield (kg/ha/Yr)	$21,924.2 \pm 895.6^a$	$20,465.0 \pm 1,685.2^a$	$18,595.0 \pm 1,028.6^b$

Values sharing the same superscript letter(s) within a row are not significantly different at the 5% probability level (p > 0.05).

The SGR followed the same pattern, with the highest value in T_1 ($1.15 \pm 0.01\%$ day^{-1}), followed by T_2 ($1.13 \pm 0.02\%$ day^{-1}) and T_3 ($1.09 \pm 0.01\%$ day^{-1}). Although the numerical differences were small, the significant reduction in T_3 indicates lower growth efficiency at the highest level of fish meal replacement. This may result from reduced digestibility and an imbalance in essential amino acids, particularly when plant proteins are used without adequate processing or amino acid supplementation. In support of this explanation, El-Dakar *et al.*, (2023) found that a fishmeal-free fermented soybean meal diet alone reduced growth and feed utilization, whereas combining the alternative protein with corn gluten and methionine improved final weight, weight gain, and SGR. The results also demonstrate that the quality and processing of alternative protein sources are as important as the replacement level (Wang *et al.*, 2024; Phinyo *et al.*, 2024). These findings suggest that the poorer performance of T_3 may potentially be improved through processing methods that enhance the digestibility and nutritional quality of MOC. Survival also differed significantly ($p < 0.05$) among treatments, declining from $89.05 \pm 2.89\%$ in T_1 to $84.25 \pm 4.19\%$ in T_2 and $81.10 \pm 3.73\%$ in T_3. The lower survival in T_3 may reflect cumulative nutritional stress associated with the higher level of fish meal replacement. Reduced nutrient availability can affect fish condition and stress tolerance, particularly during a long production cycle. However, survival is also influenced by pond environmental conditions, disease exposure, stocking density, and management. The generally high survival across treatments indicates that all diets were broadly acceptable, although the lower value in T_3 suggests that its higher MOC inclusion was less suitable for maintaining optimal fish performance. These results are comparable with recent studies reporting high survival of Nile tilapia fed diets containing alternative plant-based protein sources (Rahman *et al.*, 2023; Boonmee *et al.*, 2024).

Yield followed the same pattern as growth and survival. T_1 achieved the highest production of $10,962.1 \pm 447.8$ kg ha^{-1} per six months, equivalent to an extrapolated annual yield of $21,924.2 \pm 895.6$ kg ha^{-1}, while T_2 produced a statistically similar yield. In contrast, T_3 produced the lowest annualized yield ($18,595.0 \pm 1,028.6$ kg ha^{-1} year^{-1}). The superior production in T_1 was primarily associated with its higher individual growth and survival. Similar production trends have been reported in recent tilapia studies under improved feeding and management practices (Rahman *et al.*, 2023; Boonmee *et al.*, 2024; FAO, 2024). Thus, small reductions in growth and survival can lead to substantial production losses at the hectare level. Overall, the present study indicates that moderate fish meal replacement can maintain satisfactory growth, survival, and production, whereas excessive replacement may reduce performance. The results are consistent with recent evidence showing that plant-based proteins can effectively replace a portion of fish meal, but optimal replacement depends on ingredient quality, digestibility, amino acid balance, and processing (Magbanua & Ragaza, 2024; Maundu *et al.*, 2024). Therefore, T_2 appears to provide a practical balance between reducing fish meal use and maintaining growth performance, while the higher MOC inclusion in T_3 may require further nutritional improvement, before being recommended for intensive tilapia production.

Feed performance

Feed Conversion Ratio (FCR)

The feed conversion ratio (FCR) of tilapia differed significantly ($p<0.05$) among dietary treatments, indicating that the level of fish meal replacement influenced feed utilization efficiency (Table 4). The highest FCR was recorded in T_1 (1.95 ± 0.03), which was significantly higher than those in T_2 (1.72 ± 0.04) and T_3 (1.68 ± 0.05), while T_2 and T_3 did not differ significantly ($p>0.05$). The improved FCR in T_2 and T_3 may be attributed to the satisfactory digestibility and balanced nutrient composition of diets containing plant-based protein sources, which can partially replace fish meal without compromising feed utilization (El-Sayed, 2020; Hua, 2021; Rahman *et al.*, 2023; Boonmee *et al.*, 2024). The favorable FCR in T_2 further suggests that the diet containing 25% fish meal and 30% MOC provided an appropriate balance of nutrients for efficient feed utilization. Similar findings have been reported in Nile tilapia fed properly formulated plant-protein diets, particularly where nutrient digestibility was improved through appropriate formulation or supplementation (Rahman *et al.*, 2023; Soltan *et al.*, 2023). Although T_3 recorded the lowest FCR (1.68 ± 0.05), it produced lower growth and yield than T_1 and T_2, indicating that a lower FCR alone does not necessarily result in greater overall production. The higher MOC inclusion may have affected dietary palatability, amino acid balance, nutrient availability, digestibility, or anti-nutritional factors, thereby limiting growth and production. Similar responses have been reported in Nile tilapia, where moderate fish meal replacement maintained satisfactory biological performance, whereas higher replacement levels reduced performance (Hua, 2021; Reda *et al.*, 2022; Ayyat *et al.*, 2023; Rahman *et al.*, 2023; Boonmee *et al.*, 2024). The FCR values obtained in the present study (1.68–1.95) were comparable with those reported in recent studies using alternative protein sources, including microalgae, single-cell protein, insect meal, and plant-based ingredients (Ogola *et al.*, 2020; Sarker *et al.*, 2020; Yossa *et al.*, 2021; Abdel-Latif *et al.*, 2022; Wuertz *et al.*, 2022). However, FCR can vary with fish size, dietary composition, culture system, stocking density, feeding practices, and pond management; therefore, direct comparisons among studies should be interpreted cautiously (Rahman *et al.*, 2023; FAO, 2024).

Overall, the results indicate that partial replacement of fish meal with MOC improved feed utilization, with T_2 providing the most favorable balance between FCR, growth, and production. Although T_3 achieved the lowest FCR, its reduced growth and yield suggest that increasing MOC beyond the moderate replacement level did not provide an overall production advantage. Therefore, moderate and nutritionally balanced fish meal replacement appears more suitable for maintaining efficient feed utilization, growth, survival, and production under pond culture conditions. The optimization of alternative-protein diets should consequently consider FCR together with feed intake, growth, survival, yield, and economic return rather than relying on FCR alone.

Table 4. Feed Conversion Ratio (FCR) of tilapia under different treatments in experimental ponds.

Parameter	**Treatments**		
	T_1	**T_2**	**T_3**
FCR	1.95 ± 0.03^a	1.72 ± 0.04^b	1.68 ± 0.05^b

Values sharing the same superscript letter(s) within a row are not significantly different at the 5% probability level (p > 0.05).

Economic analysis of tilapia farming

The economic performance of tilapia (*Oreochromis niloticus*) showed that partial replacement of fish meal (FM) with mustard oil cake (MOC) significantly influenced production costs and profitability (Table 5). As the diets were isonitrogenous and stocking density, initial fish weight, and culture duration were identical, the observed differences were mainly associated with feed formulation, utilization, and resulting fish production. A clear trade-off was observed: T_1 produced the highest gross return, whereas T_2 achieved the highest net profit and cost-benefit ratio (CBR). Feed was the major production cost, accounting for 82.1, 78.4, and 77.1% of total costs in T_1, T_2, and T_3, respectively. Feed cost declined from BDT 642,483.33 ha^{-1} in T_1 to BDT 508,421.67 ha^{-1} in T_2 and BDT 473,178.67 ha^{-1} in T_3, representing reductions of 20.9 and 26.4% at 16.7 and 33.3% FM replacement, respectively. Consequently, total production cost declined from BDT 782,495.33 ha^{-1} in T_1 to BDT 648,221.67 ha^{-1} in T_2 and BDT 614,078.67 ha^{-1} in T_3, or by 17.1 and 21.5%, respectively. As seed cost remained constant, these savings mainly resulted from lower feed expenditure. Similar reductions in feed costs using alternative, locally available protein sources have been reported by Mmanda *et al.*, (2020) and Badran *et al.*, (2024).

Table 5. Economic Analysis of Tilapia *(Oreochromis niloticus)* farming in experimental ponds under different treatments.

Parameters	**Treatments**		
	T1	**T2**	**T3**
Variable Cost (BDT / ha / 6 months)			
Seed (including transportation)	$98,800 \pm 0.00^a$	$98,800 \pm 0.00^a$	$98,800 \pm 0.00^a$
Feed	$642,483.33 \pm 503.32^a$	$508,421.67 \pm 901.85^b$	$473,178.67 \pm 1,527.53^c$
Fixed Cost (BDT / ha / 6 months)			
Lime	$10,212.00 \pm 0.00^c$	$10,500.00 \pm 0.00^b$	$10,600.00 \pm 0.00^a$
Fertilizer	$5,000.00 \pm 0.00^a$	$5,000.00 \pm 0.00^a$	$5,000.00 \pm 0.00^a$
Labor	$11,000.00 \pm 0.00^b$	$10,500.00 \pm 0.00^c$	$11,500.00 \pm 0.00^a$
Sampling and Harvesting	$15,000.00 \pm 0.00^a$	$15,000.00 \pm 0.00^a$	$15,000.00 \pm 0.00^a$
Total Cost (BDT/ha)	$782,495.33 \pm 503.32^a$	$648,221.67 \pm 901.85^b$	$614,078.67 \pm 1,527.53^c$
Total Return (BDT/ha / 6 months)	$1,315,452 \pm 53,736^a$	$1,227,900 \pm 101,112^a$	$1,115,700 \pm 61,716^b$
Net Profit (BDT/ha)	$532,956.67 \pm 53,233^b$	$579,678.33 \pm 100,210^a$	$501,621.33 \pm 60,188^c$
Cost-Benefit Ratio (CBR)	0.68 ± 0.07^b	0.89 ± 0.15^a	0.82 ± 0.10^{ab}

Values sharing the same superscript letter(s) within a row are not significantly different at the 5% probability level (p > 0.05).

Despite its highest production cost, T_1 generated the highest gross return (BDT 1,315,452 ± 53,736 ha^{-1}), followed by T_2 (BDT 1,227,900 ± 101,112 ha^{-1}) and T_3 (BDT 1,115,700 ± 61,716 ha^{-1}). Gross return was 7.1% lower in T_2 and 15.2% lower in T_3 than in T_1, reflecting their lower fish production. Similar relationships between biological performance and economic returns have been reported by Ouko *et al.*, (2024) and Munguti *et al.*, (2024), indicating that the lowest-cost diet does not necessarily provide the highest return. Importantly, T_2 achieved the highest net profit (BDT 579,678.33 ± 100,210 ha^{-1}), approximately 13.0% higher than T_1, while T_3 recorded the lowest net profit (BDT 501,621.33 ± 60,188 ha^{-1}). In T_2, the 16.7% FM replacement reduced feed expenditure by approximately BDT 134,062 ha^{-1}, exceeding its reduction in gross return of approximately BDT 87,552 ha^{-1}. Thus, feed-cost savings outweighed the lower revenue, indicating that moderate FM replacement provided the best balance between cost and production. This agrees with Limbu *et al.*, (2022) and Ouko *et al.*, (2024), who also reported improved economic efficiency at moderate rather than excessive replacement levels.

Although T_3 had the lowest feed and total production costs, its net profit was reduced because its 21.5% cost reduction was accompanied by a 15.2% decline in gross return and lower growth and yield. This suggests that increasing MOC beyond the T_2 level may have exceeded the optimum nutritional and economic balance. A similar pattern was reported by Badran *et al.*, (2024), where excessive plant-derived protein inclusion could reduce biological performance. The CBR further confirmed the economic superiority of T_2, increasing from 0.68 $\pm$ 0.07 in T_1 to 0.89 $\pm$ 0.15 in T_2 and 0.82 $\pm$ 0.10 in T_3. Compared with T_1, CBR improved by 30.9% in T_2 and 20.6% in T_3. Thus, despite its lower production cost, T_3 did not achieve the highest CBR because reduced production offset the additional feed-cost savings. Similar improvements in economic performance following the use of alternative protein sources and partial replacement of fish meal have been reported by Wachira *et al.*, (2021), Limbu *et al.*, (2022), and Badran *et al.*, (2024). In particular, Badran *et al.*, (2024) reported reductions in feed cost of up to 10.32% per kilogram of fish gain through the incorporation of a blend of oilseed meals in Nile tilapia diets. However, economic performance may vary with local feed and fish prices, ingredient availability, stocking density, culture duration, feeding practices, survival, FCR, and market conditions (Mmanda *et al.*, 2020; Ouko *et al.*, 2024). Therefore, the optimum replacement level should be determined under local production and price conditions.

Overall, the 16.7% FM-protein replacement treatment (T_2: 25% FM and 30% MOC) provided the best balance between production and cost, achieving the highest net profit and CBR. T_1 maximized production and gross revenue but incurred higher feed costs, whereas T_3 minimized costs but experienced lower production and profitability. These findings support the use of moderate FM replacement with nutritionally balanced alternative proteins to improve the economic efficiency of monosex tilapia farming (Mmanda *et al.*, 2020; Limbu *et al.*, 2022; Badran *et al.*, 2024; Ouko *et al.*, 2024; Munguti *et al.*, 2024). Economic optimization should therefore consider feed cost, FCR, growth, yield, survival, gross return, net profit, and CBR rather than feed cost alone.

Conclusion and recommendation

The present study demonstrates that partial replacement of fish meal with mustard oil cake (MOC) significantly influences the economic performance of tilapia farming. Among the treatments evaluated, T_2 (25% fish meal and 30% MOC; 16.7% fish meal replacement) resulted in significantly higher ($P<0.05$) net profit and cost–benefit ratio (CBR), indicating it as the most economically viable dietary formulation under the experimental conditions. The study also highlights the potential of alternative plant-based protein sources in reducing feed costs while maintaining satisfactory production performance, thereby improving the overall economic efficiency of tilapia farming systems in Bangladesh. In addition, the use of fish meal replacement diets contributes to more sustainable aquaculture practices with potential environmental benefits, including reduced pressure on marine feed resources and lower greenhouse gas (GHG) emissions associated with feed production. However, this study focused primarily on the partial replacement of fish meal with mustard oil cake and its effects on production performance, economic returns, and greenhouse gas (GHG) emissions. Future research should investigate complementary management strategies, including optimized feeding frequency, the use of functional feed additives, restricted feeding regimes, improved pond waste and nutrient management, and enhanced culture system designs. Integrating these approaches could further improve resource use efficiency, reduce environmental impacts, and support the development of climate-smart and sustainable tilapia production systems under farmer-managed pond conditions.

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Authors contribution statement: Conceptualization, methodology, investigation, analysis and original draft preparation: M.H.A.; writing—review and editing, supervision, and technical guidance: M.A.H. All authors have read and agreed to the published version of the manuscript.

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