

Evaluating Moringa Leaf Meal for Sustainable and Cost-Effective Fish Meal Substitution

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DOI: <https://doi.org/10.51244/IJRSI.2025.120800380>

Received: 11 Sep 2025; Accepted: 17 Sep 2025; Published: 16 October 2025

ABSTRACT

Aquaculture is the fastest-growing food production sector globally, yet it remains heavily dependent on fish meal-based feeds. Moringa (*Moringa oleifera*) leaves, rich in protein, essential amino acids, vitamins, and minerals, have emerged as a promising substitute for fish meal. This study evaluated the efficacy of Moringa Leaf Meal (MLM) as a partial fish meal (FM) replacement in diets for rohu (*Labeo rohita*) fingerlings under controlled laboratory conditions at the Department of Aquaculture, Bangladesh Agricultural University, Mymensingh. A 60-day feeding trial was conducted using three dietary treatments: T₁ (Control, 0% MLM), T₂ (10% MLM), and T₃ (20% MLM), with three replicates per treatment. Rohu fingerlings (11.47 ± 2.0 g) were stocked in nine 90 L plastic drums, maintained with daily 25% water exchange and continuous aeration. Fish were fed experimental diets at 5% body weight twice daily, and growth performance, water quality parameters, and feed cost were monitored throughout the study. All treatments achieved 100% survival. Growth performance, measured as mean length and weight gain, was significantly higher ($p < 0.05$) in fish fed T₂ and T₃ diets compared to the control, with T₂ exhibiting the best overall performance. Proximate composition analysis revealed higher crude protein and lipid content but lower ash and fiber content in rohu fingerlings with increasing MLM inclusion. Feed cost analysis showed that T₃ had the lowest feed cost, while T₁ was the most expensive. These findings suggest that incorporating 10% Moringa Leaf Meal in rohu diets is a cost-effective and sustainable strategy that enhances growth performance without compromising fish health or welfare.

Keywords: Aquaculture, Moringa (*Moringa oleifera*), Rohu (*Labeo rohita*), Sustainable feed

INTRODUCTION

The growing global demand for fish, driven by both increasing consumption and the projected rise in world population, has put immense pressure on traditional fisheries, prompting the expansion of aquaculture as a key solution to meet these needs (Bjørndal et al., 2024; DOF, 2024). As the aquaculture industry continues to grow, ensuring a reliable and cost-effective source of protein for fish feed becomes paramount. Fish meal (FM) has long been the primary protein source in aquafeeds, valued for its balanced amino acid profile, digestibility, and palatability (Hussain et al., 2024). However, the rising cost, declining supply, and environmental concerns (Hasan et al., 2021, Hasan et al., 2022, Fatema et al., 2023; Hasan et al., 2023; Hasan et al., 2024) associated with FM have highlighted the need for alternative protein sources.

Plant-based proteins have garnered significant attention as viable substitutes for FM in aquafeeds due to their sustainability, availability, and lower cost. Among these, *Moringa oleifera*, a highly nutritious plant known for

its impressive protein content and various health benefits, has emerged as a promising candidate. Moringa leaves are rich in essential amino acids, vitamins, and minerals, making them a potentially invaluable resource for aquaculture feeds (Hany et al., 2022).

Nutritionally, Moringa is a powerhouse. The leaves contain approximately 25–30% crude protein on a dry matter basis, which is comparable to other high-protein plant sources (Gopalakrishnan et al., 2016). Moringa is also rich in essential amino acids (EAAs) such as leucine, lysine, and methionine, which are crucial for fish growth and development (Hany et al., 2022). These amino acids help promote the synthesis of proteins in the body, leading to enhanced muscle mass and overall growth performance in fish (El-Kassas et al., 2020). Furthermore, Moringa leaves contain a variety of vitamins, including Vitamin A, C, and E, which are essential for immune function, antioxidant protection, and overall health (Gopalakrishnan et al., 2016). The presence of vital minerals such as calcium, iron, magnesium, and potassium in Moringa is also important for supporting the fish's bone development, metabolic processes, and overall wellbeing.

In addition to its rich nutritional profile, Moringa is abundant in phytochemicals such as flavonoids, carotenoids, and phenolic acids, which have antioxidant, anti-inflammatory, and antimicrobial properties (Gopalakrishnan et al., 2016). These bioactive compounds can contribute to improved disease resistance and immunity in fish, making Moringa not just a protein source but also a functional feed additive (Zhang et al., 2020). Studies have shown that Moringa supplementation can enhance the growth performance, feed conversion efficiency, and immune responses of various fish species, including Nile tilapia, rohu, and catfish.

This study aims to evaluate the feasibility of using Moringa leaf meal (MLM) as a sustainable and cost-effective alternative to fish meal in the diet of aquaculture species, specifically focusing on its impact on growth performance, feed conversion ratio, and overall fish health. By exploring MLM as a partial replacement for FM, the research seeks to contribute to the development of more sustainable aquafeed formulations that can reduce reliance on traditional fish meal, support aquaculture growth, and mitigate environmental impacts.

MATERIALS AND METHODS

The experiment was conducted in the Aquaponics Laboratory of the Department of Aquaculture, Faculty of Fisheries, Bangladesh Agricultural University (BAU), Mymensingh. The study spanned 60 days, from 20th September to 20th November 2018. Rohu (*Labeo rohita*) fingerlings with an average initial weight of 11.47 (± 2.0) g were selected for the experiment. The study involved three treatments, based on the inclusion level of Moringa leaf meal (MLM) to replace fish meal (FM) as T₁ (Control): 0%, T₂: 10% and T₃: 20% MLM inclusion. Each treatment was replicated thrice, resulting in nine circular fish-holding tanks, each containing 90 liters of water.

The experimental tanks were equipped with 18-watt air pumps and air stones for continuous oxygenation and covered with thin nylon nets to prevent fish from jumping or being exposed to predators. These tanks were supplied with continuous electricity to ensure optimal oxygen levels throughout the study. Moringa leaf meal (MLM) was incorporated into experimental diets at 0% (control), 10%, and 20% inclusion levels, with fish meal replaced by MLM in the T₂ and T₃ diets. Moringa leaves, sourced from Litu Moringa Estate, were cleaned, blanched in boiling water for 2 minutes, and soaked in chilled water to stop the cooking process. After air-drying and further dehydration, the leaves were ground into fine powder and stored in airtight containers to maintain their nutritional integrity for feed preparation and subsequent analysis (Table 1).

Table 1. The proximate composition of moringa leaf meal (MLM)

Nutrients	Composition (%)
Moisture	12.86
Crude lipid	2.3

Crude protein	27.57
Crude fiber	12.21
Ash	4.25
NFE	40.81

The fish feed was formulated to progressively replace fishmeal (FM) with moringa leaf powder (MLM) while maintaining a crude protein content of 30% across all diets. MLM was incorporated at three levels: 0% (control), 10%, and 20%, replacing equivalent amounts of FM (Table 2). Locally available ingredients such as wheat flour, mustard oil cake, soybean meal, fish meal, moringa leaf meal, soybean oil, rice bran, and a vitamin-mineral premix were used to create the experimental diets (Table 3). The ingredients were carefully weighed and mixed by hand with enough water to form a smooth mixture, which was then pelletized using a pellet die machine. The prepared pellets were dried in a homemade oven for 24 hours to reduce moisture content. Afterward, the experimental diets underwent proximate composition analysis, following standard procedures from AOAC (2000) and using triplicate samples for accuracy.

Table 2. Feed Ingredients for Formulating Test Diets Containing 30% Crude Protein for Rohu Fingerlings

Ingredients	T ₁ (Control; 0% FM replaced with MLM)	T ₂ (10% FM replaced with MLM)	T ₃ (20% FM replaced with MLM)
Moringa leaf powder	0	3	6
Fish meal	30	27	24
Rice bran	25	25	25
Soybean meal	10	15	15
Mustard oil cake	15	13	14
Wheat flour	15	12	11
Soybean oil	3	3	3
Vitamins and mineral premix	2	2	2
Total	100	100	100

Table 3. Proximate composition analysis of moringa (*Moringa oleifera*) leaf-based fish feeds

Parameters	Feed with 0% MLM (T ₁)	Feed with 10% MLM (T ₂)	Feed with 30% MLM (T ₃)
Moisture	12.91	12.55	12.58
Crude protein	30.89	30.84	29.76
Crude lipids	4.81	4.95	5.21
Ash	12.33	12.38	11.84
Fiber	6.22	6.56	6.81

NFE	32.83	32.71	33.91
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The preparation of fish tanks involved washing, disinfecting, and drying to ensure cleanliness and eliminate harmful substances. Tanks were equipped with air pumps and filled with 90 liters of water. Rohu fingerlings were sourced from a hatchery, acclimatized in the lab for 15 days, and starved for 24 hours before the experiment to standardize their digestive system. They were fed handmade feeds at a rate of 5% of their body weight twice a day. Water quality parameters, including temperature, pH, and dissolved oxygen, were monitored regularly. Fish length and weight were measured bi-weekly, and growth performance was evaluated based on length gain, weight gain, specific growth rate (SGR), food conversion ratio (FCR), survival rate, and fish production. A low pH stress tolerance test was conducted by exposing fish to pH 3 water, and disease treatment involved a saltwater bath to control infection. Feed cost was calculated based on ingredient prices, and proximate composition analysis of fish and diets followed AOAC standards (Table 4).

Table 4: The price of fish feed ingredients at the local market

Feed ingredients	Price(tk)/Kg
Moringa leaf meal	30
Fish meal	80
Wheat flour	25
Soybean meal	42
Rice bran	35
Mustard oil cake	35
Soybean oil	80
Vitamin and mineral premix	100

Collected data were entered into the computer for statistical analysis. One-way analysis of variance (ANOVA) was performed using SPSS (Statistical Package for Social Science) to evaluate the influence of different treatments on the parameters. Comparison between treatment means was carried out using Duncan's multiple range tests to analyze the significance of variations between the treatments. All statistical analyses were performed using MS Excel 2007 (version 7.0). The results are presented as mean $\pm$ standard deviation (SD).

RESULTS

Growth performance

The growth performance of rohu fingerlings (*Labeo rohita*) was assessed over a 60-day period using three different feed treatments, including two diets supplemented with moringa leaf meal (MLM) and a control feed. The growth parameters were evaluated based on length (cm) and weight gain (g). Graphical representations of the growth performance of rohu fingerlings are presented in Figures 12 to 18. The results demonstrated a noticeable increase in both length and weight over time, with growth observed on various sampling dates (Tables 5 and 6). Key indicators of growth performance, including initial weight, final weight, percentage weight gain, specific growth rate (SGR) (% per day), survival rate (%), and fish production (kg/ha/60 days), were calculated for each treatment and are summarized in Table 7. These results highlight the potential benefits of using moringa leaf meal-based diets for the nursing of rohu fingerlings.

Table 5. The length increased of rohu fingerlings during the experiment

Sampling Date	Feed with 0% MLM replaced by FM (T ₁)	Feed with 10% MLM replaced by FM (T ₂)	Feed with 20% MLM replaced by FM (T ₃)	F Value	p- Value	Level of sig.
20.09.2018	11.32(±0.23) a	11.50(±0.15) a	11.64(±0.02) a	3.125	0.12	NS
05.10.2018	11.51(±0.18) a	11.73(±0.14)ab	11.89(±0.02) b	3.209	0.11	NS
20.10.2018	11.75(±0.17) a	12.08(±0.14) b	12.25(±0.11) b	9.539	0.02	*
05.11.2018	12.05(±0.19) a	12.48(±0.14) b	12.58(±0.09) b	10.817	0.01	*
20.11.2018	12.40(±0.18) a	12.92(±0.21) b	12.87(±0.07) b	8.560	0.02	*

*a, b, c means with different superscripts within the same row differ significantly *=Significant (P>0.05), *
*=Significant (P>0.01)

Table 6. The weight increased of rohu fingerlings during the experiment

Sampling Date	Feed with 0% MLM replaced by FM (T ₁)	Feed with 10% MLM replaced by FM (T ₂)	Feed with 20% MLM replaced by FM (T ₃)	F Value	p- Value	Level of sig.
20.09.2018	12.13(±0.04) ^a	12.34(±0.05) ^b	12.39(±0.01) ^b	3.063	0.00	**
05.10.2018	12.71(±0.11) ^a	13.18(±0.24) ^b	13.26(±0.13) ^b	8.518	0.02	*
20.10.2018	13.59(±0.38) ^a	14.35(±0.24) ^b	14.37(±0.27) ^b	6.314	0.03	*
05.11.2018	14.56(±0.46) ^a	15.70(±0.23) ^b	15.66(±0.24) ^b	11.307	0.01	**
20.11.2018	15.51(±0.29) ^a	16.81(±0.21) ^b	16.65(±0.17) ^b	27.924	0.01	**

*a,b,c means with different superscripts within the same row differ significantly *=Significant (P>0.05), *
*=Significant (P>0.01)

At the start of the experiment, there were no significant differences ($P > 0.05$) in the initial lengths of the rohu fingerlings across the three treatments (T₁, T₂, and T₃). Over the 60-day study period, the highest mean length gain was observed in T₂ at 12.92 (±0.21) cm, followed closely by T₃ at 12.87 (±0.07) cm and T₁ at 12.40 (±0.18) cm (Table 5). The mean length gain was significantly higher in T₂ compared to the control, with a difference of 1.42 cm. The lowest mean length gain was observed in T₁, with a difference of 1.08 cm. The graphical representation of the mean length gain. During the 60-day experimental period, the highest percent length gain was observed in T₂ at 12.41 (±1.34)%, compared to T₃ and T₁. The lowest percent length gain was recorded in T₁ at 9.55 (±0.99)%. The graphical illustration of percent length gain.

The highest mean final weight was 16.81 (±0.21) g in T₃, while the lowest mean final weight was 15.51 (±0.29) g in T₁. The mean weight gain in the treatments was as follows: T₁, 3.38 (±0.24) g; T₂, 4.46 (±0.19) g; and T₃, 4.25 (±0.15) g. A significant ($P < 0.05$) difference in mean final weight gain was observed among the three treatments (T₁, T₂, and T₃). Over the 60-day experimental period, the highest percent weight gain was recorded in T₂ at 36.17 (±1.56)%, followed by T₃, and the lowest percent weight gain was observed in T₁ at 27.90 (±1.94)%.

Table 7. Growth response and feed utilization of rohu fingerlings fed the prepared feed containing moringa leaf meal

Parameters	Feed with 0% MLM replaced by FM (T ₁)	Feed with 10% MLM replaced by FM (T ₂)	Feed with 20% MLM replaced by FM (T ₃)	F Value	p- Value	Level of sig.
Initial length (cm)	11.32(±0.23) a	11.50(±0.15) ^a	11.64(±0.02) a	3.125	0.12	NS
Final length (cm)	12.87(±0.07) ^b	12.92(±0.21) ^b	12.40(±0.18) a	27.93	0.01	**
% length gain	9.55(±0.99) ^a	12.41(±1.34) ^b	10.53(±0.41) ^{ab}	06.39	0.03	*
Initial weight (g)	12.13(±0.04) ^a	12.34(±0.05) ^a	12.39(±0.01) ^a	3.063	0.45	NS
Final wt (g)	16.65(±0.17) ^b	16.81(±0.21) ^b	15.51(±0.29) ^a	30.11	0.01	**
% wt gain	27.90(±1.94) ^b	36.17(±1.56) ^b	34.30(±1.23) ^a	21.74	0.02	**
FCR	1.99(±0.28) ^b	1.02(±0.22) ^a	1.17(±0.21) ^a	8.65	0.13	NS
SGR (%/day)	0.98(±0.21) ^a	1.01(±0.08) ^a	0.94(±0.18) ^a	0.13	0.88	NS
Survival (%)	100	100	100	-	-	-
Production(kg/m ³)	12.81	18.11	15.89	-	-	-

*Mean (±SD); Significant level indicates in a rightward and mean with same superscript values are insignificantly different (P>0.05).

No significant difference in the mean specific growth rate (SGR, % per day) was observed among the treatments (T₁, T₂, and T₃), indicating statistical similarity across all groups. The mean SGR values recorded were 0.98% for T₁, 1.01% for T₂, and 0.94% for T₃. Among the treatments, T₂ showed the highest mean SGR value (1.01%), while T₃ exhibited the lowest mean SGR value (0.94%). No mortality was recorded during the 60-day experimental period, resulting in a 100% survival rate for rohu fingerlings across all treatments (Table 7). The fish production of rohu fingerlings ranged from 1,282 to 1,811 kg/ha over the 60-day period (Table 7). The highest production was observed in the T₂ treatment, with 1,811 kg/ha, followed by the control treatment and T₃. The lowest production was recorded in T₁, at 1,282 kg/ha. A graphical representation of fish production.

The results of the low pH stress test are presented in Figure 1. Fish-fed diets with 20% MLM replacing fish meal (FM) in T₃ and 10% MLM replacing FM in T₂ showed significantly (P < 0.05) higher tolerance to low pH stress compared to T₁ (control), which was fed a diet with 0% MLM replacing FM. The time to 50% mortality (LD₅₀) was significantly lower in T₁, indicating reduced stress tolerance in fish from the control group. This suggests that MLM inclusion in the diet enhanced the resilience of rohu fingerlings to acidic stress conditions.

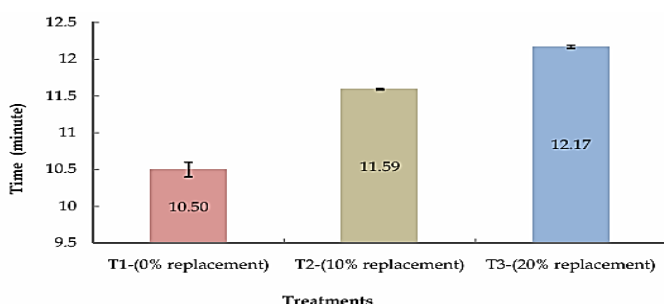


Figure 1. Time to 50% mortality (LD₅₀) in low pH stress test (vertical bar of each treatment represents standard deviation).

Efficient feed utilization depends on the cost and acceptability of the feed by the fish. To determine the most efficient feed among the three diets tested for rohu fingerlings, the food conversion ratio (FCR) and feed costs were evaluated. The FCR values of the three experimental diets were calculated at the end of the 60-day study period. The highest FCR value was recorded in T1 at 3.99 (± 0.28), indicating lower feed efficiency in this treatment. The lowest FCR value was observed in T2 at 3.02 (± 0.22), although this difference was not statistically significant compared to other treatments (Table 7, Figure 19). This suggests that the T2 diet, with 10% MLM replacing fish meal, was the most efficient in terms of feed conversion among the tested diets.

Cost of the experimental diets

The cost of the three experimental diets was calculated based on the market prices of the ingredients used. The feed costs were as follows: T1 (control): 50.35 tk/kg; T₂ (10% MLM replacing fish meal): 49.50 tk/kg; T₃ (20% MLM replacing fish meal): 48.10 tk/kg. Among the diets, T₃ was the most cost-effective, with the lowest feed cost (48.10 tk/kg), as it incorporated 20% MLM as a replacement for fish meal. Conversely, the control feed (T1), which contained 100% fish meal, was the most expensive due to the higher inclusion level of fish meal. The cost of feed decreased as the level of MLM inclusion increased, highlighting the economic benefits of using moringa leaf meal in fish feed formulations (Figure 2).

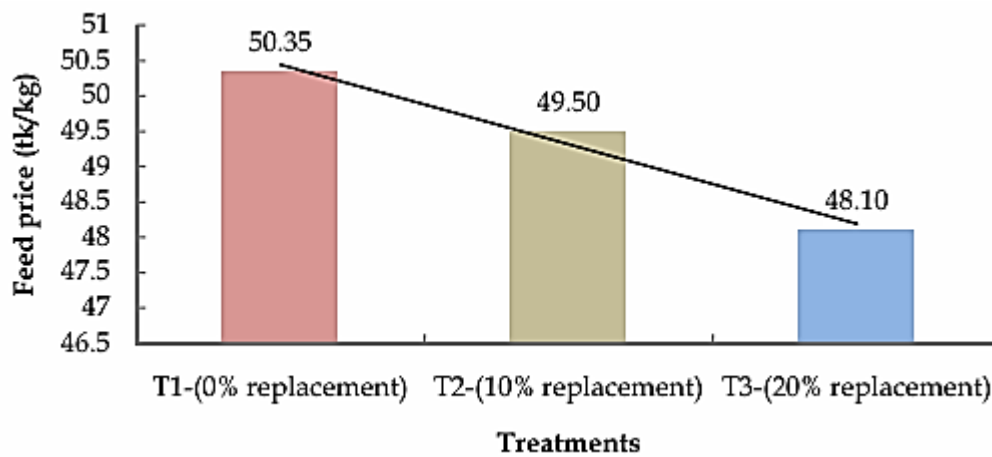


Figure 2. The cost of different diets (tk/kg) in the present study

Proximate composition of Rohu

The proximate composition of the experimental rohu fingerlings, which were fed the different diets, was analyzed at the end of the experiment in the Aquaculture Nutrition Laboratory. The results of the proximate composition, including moisture, protein, lipid, and ash content, are presented in Table 8. These results provide insights into the nutritional quality of the fish based on the different feeding treatments.

Table 8. The proximate composition of rohu fingerlings (% moisture basis) with experimental diets

Parameters	Feed with 0% MLM replaced by FM (T ₁)	Feed with 10% MLM replaced by FM (T ₂)	Feed with 20% MLM replaced by FM (T ₃)
Moisture	78.07(± 0.31) ^b	76.60(± 0.08) ^a	77.73(± 0.05) ^b
Crude protein	14.08(± 0.02) ^a	15.14(± 0.04) ^c	14.55(± 0.03) ^b
Crude lipid	3.07(± 0.18) ^a	3.91(± 0.06) ^c	3.31(± 0.04) ^b
Ash	3.87(± 0.04) ^b	3.18(± 0.14) ^a	3.05(± 0.05) ^a

NFE	1.45(±0.07)ab	1.15(±0.09)ac	0.88(±0.11)b
Carbohydrate	0.30 (±0.06) ^b	0.77 (±0.02) ^a	0.79 (±0.03) ^a

No significant differences were observed in the moisture content among the treatments. The highest moisture content was found in T₁ (78.07 ± 0.31%), while the lowest moisture content was recorded in T₂ (76.60 ± 0.08%) (Table 8). The crude protein content of rohu fish ranged from 14.08 (±0.02) to 15.14 (±0.04). The highest protein content was found in T₂, while the lowest was recorded in T₁ (Table 8). The crude lipid content of the rohu fish ranged from 3.07 (±0.18) to 3.91 (±0.06). The highest lipid content (3.91 ± 0.06%) was found in T₂, whereas the lowest value (3.07 ± 0.18%) was observed in T₁ (Table 8). The ash content of the rohu fish ranged from 3.05 (±0.05) to 3.87 (±0.04), with no significant differences observed among the treatments (Table 8). The Carbohydrate content in the fish varied from 0.30 (±0.06) to 0.79 (±0.06), with the highest value found in T₃. T₂ and T₃ treatments showed similar carbohydrate content, with T₃ having the highest and T₁ showed a significant difference with other two treatments (Table 8).

Water quality

Maintaining optimal water quality is essential for maximizing fish production in aquaculture. The physico-chemical parameters of water, including temperature (°C), dissolved oxygen (mg/L), pH, ammonia (mg/L), nitrate (mg/L), and nitrite (mg/L), were within the suitable range for rearing rohu fingerlings. The water quality parameters measured in the experimental tanks throughout the study period are provided in Table 9. These values indicate that water conditions were well-maintained, supporting healthy fish growth during the experiment.

Table 9. The water quality parameters of different treatments during the experimental period

Parameters	Feed with 0% MLM replaced by FM (T ₁)	Feed with 10% MLM replaced by FM (T ₂)	Feed with 20% MLM replaced by FM (T ₃)
Temperature (°C)	25.52(±0.59)	25.09(±0.38)	25.23(±0.34)
Dissolved Oxygen (mg/L)	5.6(±0.50)	5.53(±0.20)	5.45(±0.18)
pH	7.62(±0.05)	7.61(±0.08)	7.66(±0.08)
EC (µs/cm)	360(±2.89)	366.67(±1.02)	371(±3.06)
TDS (ppm)	182.25(±0.43)	183.44(±0.80)	184.17(±0.44)
Ammonia (mg/L)	0.08(±0.08)	0.08(±0.08)	0.08(±0.08)
Nitrate (mg/L)	1.67(±1.67)	0.89(±0.58)	0.0
Nitrite (mg/L)	0.67(±0.67)	0.0	0.0

During the study period, the water temperature ranged from 23.2°C to 30°C across the different experimental tanks. In T₁ treatment, the temperature varied from 23.4°C to 30°C, in T₂ treatment from 23.2°C to 28°C, and in T₃ treatment from 23.4°C to 29°C (Table 9). The highest recorded temperature was 30°C in T₁ treatment on 20th September 2018, while the lowest was 23°C in T₂ treatment on 11th October 2018.

The dissolved oxygen (DO) ranged from 2.9 mg/L to 6.7 mg/L throughout the study period (Table 9). Significant variation in DO levels was observed at different times across the treatments. The highest DO concentration (6.7 mg/L) was recorded in T₂ treatment on 11th October 2018. The lowest DO concentration (2.9 mg/L) was observed in T₃ treatment on 20th September 2018, during a period when the conditions were poor due to a power outage overnight. The average pH values fluctuated between 7.48 and 7.75 across the

treatments during the experimental period. The mean pH values recorded were 7.62 (± 0.05) in T₁, 7.61 (± 0.08) in T₂, and 7.66 (± 0.08) in T₃ (Table 9). No significant variation in pH was observed among the different treatments.

The mean values of electric conductivity (EC) were 360 (± 2.89) $\mu\text{S}/\text{cm}$ in T₁, 366.67 (± 1.02) $\mu\text{S}/\text{cm}$ in T₂, and 371 (± 3.06) $\mu\text{S}/\text{cm}$ in T₃ (Table 9). No significant differences in EC were observed among the treatments ($P > 0.05$). The mean TDS values were 182.25 (± 0.43) ppm in T₁, 183.44 (± 0.80) ppm in T₂, and 184.17 (± 0.44) ppm in T₃ (Table 9) and no significant differences in total dissolved solids (TDS) were found among the treatments. The mean range of ammonia (NH₃) was from 0.0 to 0.08 mg/L, nitrate (NO₃) from 0.0 to 1.67 mg/L, and nitrite (NO₂) from 0.0 to 0.67 mg/L across all treatments during the 60-day study period (Table 9). These values were within acceptable ranges, ensuring suitable water quality for the experimental rohu fingerlings.

DISCUSSIONS

The present study investigated the use of moringa leaf meal (MLM) as a substitute for fish meal (FM) in the formulation of fish feed. Approximately 208.85 g of MLM was derived from 3340 g of fresh moringa leaves, achieving a meal retention of about 16%. This yield was slightly higher than previous reports by Müller and Rebelo (2001), who obtained 12.5–15% of leaf powder from fresh moringa leaves. The variation may be attributed to differences in the drying process employed in the current study. These findings highlight the potential of MLM as a sustainable and cost-effective alternative protein source for aquafeeds, addressing challenges posed by the rising cost and environmental impact of conventional FM.

The mean and percent length gains were highest in T₂, where 10% MLM was included, compared to T₁ and T₃. The lowest values were observed in T₁, with gains of 1.08 cm and 9.55%. However, increasing the MLM level in T₃ reduced length gain, potentially due to anti-nutritional factors in moringa leaves. Similar trends were reported by Samkelisiwe and Ngonidzashe (2014) and Richter et al. (2003), indicating that high levels of MLM substitution can hinder fish growth. Weight gain and percent weight gain were significantly higher in T₂ (4.46 g and 36.17%) compared to T₁ and T₃. These findings align with studies by Ozovehe (2013) and Tagwireyi et al. (2008), which demonstrated that up to 10% MLM inclusion is optimal for growth in species such as Nile tilapia and *Clarias gariepinus*. Substitution beyond this threshold likely impacts nutrient utilization due to anti-nutrients in MLM. The SGR values, ranging from 0.94 to 1.01, showed no significant differences among treatments, with the highest observed in T₂. Comparatively lower SGR values in this study may be attributed to laboratory rearing conditions and limited nutrient utilization. Similar observations were made by Jahan et al. (2012) for soybean meal-based feeds. Survival rates were 100% across all treatments, indicating effective management practices. Previous studies by Abid and Ahmed (2009) and Jahan et al. (2012) also reported similar survival rates with partial FM replacement using plant-based proteins. The presence of antioxidants in moringa leaves likely enhanced fish immunity, contributing to the observed survival rates.

Fish production ranged from 1281 to 1811 kg/ha over 60 days, with T₂ showing the highest yield. Compared to prior studies, such as those by Islam et al. (2017) and Khan et al. (2003), this study demonstrated improved production, attributed to nutrient-rich MLM and proper culture conditions. The nutritional analysis revealed moisture, crude protein, crude lipid, ash, and carbohydrate contents within acceptable ranges. Higher protein content in fish fed MLM-based diets suggests positive nutrient utilization. Similar results were reported by Ganzon-Naret (2014) and Hossain (1988) for plant protein-based diets. Stress tolerance to low pH (pH 3) showed higher LD50 times in T₂ and T₃, indicating improved resilience due to moringa's bioactive compounds, such as phenolics and flavonoids. Gbadamosi et al. (2017) reported similar stress tolerance benefits with MLM supplementation. The cost analysis revealed that T₃ (20% MLM inclusion) was the cheapest, at 48.10 BDT/kg, compared to 50.35 BDT/kg for T₁. This cost-effectiveness underscores MLM's potential to reduce feed expenses while maintaining fish growth and health. The water quality parameters, including temperature (23.2–29°C), dissolved oxygen (2.9–6.7 mg/L), and pH (7.3–8.45), remained within suitable ranges for fish culture. These findings align with established standards (Boyd, 1982; Swingle, 1961), confirming that MLM inclusion had no adverse effects on water quality. In conclusion, the use of moringa leaf meal as a partial substitute for fish meal demonstrated promising results in terms of growth performance, cost-

effectiveness, and sustainability. Further research on optimizing inclusion levels and mitigating anti-nutritional effects could enhance its application in aquaculture.

CONCLUSION

The study demonstrated that moringa leaf meal (MLM) can be effectively used as a cost-efficient and sustainable substitute for fish meal (FM) in rohu (*Labeo rohita*) feed, with the 10% MLM-based diet (T2) showing the best growth, survival, and production performance. This approach offers a practical and affordable solution for rural fish farmers, enhancing aquaculture sustainability in Bangladesh.

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