ARTICLE IN PRESS

Aquaculture and Fisheries xxx (xxxx) xxx

Contents lists available at ScienceDirect

Aquaculture and Fisheries

journal homepage: www.keaipublishing.com/en/journals/aquaculture-and-fisheries

Original research article

Evaluating feeding strategies to improve growth and profitability in carp fattening

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ARTICLE INFO

Keywords:
Feeding restriction
Growth performance
Food conversion ratio
Economics
Good aquaculture practice

ABSTRACT

Rising feed costs and increasing climate variability, especially in drought-prone areas, threaten the sustainability of carp fattening practices in Bangladesh. This study aimed to evaluate cost-effective and climate-adaptive feeding strategies for sustainable aquaculture production. A six-month on-farm trial was conducted using three treatments: T1 (100% commercial feed), T2 (70% commercial + 30% homemade feed), and T3 (T2 with one-day-per-week feeding restriction). Standard water quality parameters were monitored throughout the trial to ensure optimal culture conditions. While growth performance and yield did not differ significantly among treatments, T3 achieved the most efficient feed conversion ratio (FCR) and significantly reduced feed cost by 15.57% compared to T1. T3 also recorded the highest profit margin 19.49% greater than T2 and 28.89% higher than T1, without compromising fish health or water quality. These findings highlight that partial replacement of commercial feed with homemade feed, coupled with mild feeding restriction, is an economically viable and environmentally sound strategy. This approach is especially suitable for smallholder farmers in climate-vulnerable regions, offering a pathway to reduce production costs and enhance resilience. Policymakers and extension services are encouraged to promote such hybrid feeding strategies to support sustainable aquaculture and improve farmer livelihoods.

1. Introduction

Carp polyculture remains the cornerstone of freshwater aquaculture in Bangladesh, providing both food security and economic sustenance for millions of rural households. In this system, multiple carp species with distinct feeding habits—such as *Catla* (surface feeder), *Labeo rohita* (column feeder), and *Cirrhinus mrigala* (bottom feeder)—are cultured together to optimize resource utilization across the vertical strata of the pond ecosystem. This practice increases productivity, minimizes interspecific competition, and enhances the ecological balance within the aquaculture environment (Hossain et al., 2022). With the intensification of aquaculture to meet rising fish demand, traditional reliance on natural food has proven insufficient. As such, the incorporation of supplementary feeding strategies has become an essential component of semi-intensive and intensive farming systems in Bangladesh.

The widespread adoption of fish feed in pond aquaculture has escalated significantly in recent years (Jewel et al., 2023). Supplementary feeding now enables rapid growth, higher stocking densities, and shorter production cycles, particularly in semi-intensive systems (Araujo et al., 2022; Noor et al., 2019). High-quality, nutritionally balanced feeds ensure enhanced feed conversion ratios (FCR), promote plankton growth through biodegradable particles, and facilitate closer

Peer review under the responsibility of Editorial Board of Aquaculture and Fisheries.
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https://doi.org/10.1016/j.aaf.2025.09.002
Received 18 June 2025; Received in revised form 31 July 2025; Accepted 12 September 2025

Please cite this article as: Md Anwar Hossain et al., *Aquaculture and Fisheries,* https://doi.org/10.1016/j.aaf.2025.09.002

observation of fish behavior during feeding. Studies such as Hossain et al. (2020) have demonstrated significant improvements in weight gain and overall yield with the use of well-formulated feed. However, the economic sustainability of such inputs remains in question, particularly for smallholder farmers. The high cost of commercial feeds, which can account for up to 60% of operational expenses (Glencross, 2020; Hossain et al., 2020), creates a substantial financial burden that may threaten long-term profitability.

To mitigate this, many farmers have begun to formulate their own aquafeeds using locally available ingredients. Although homemade feeds are more affordable, they are often nutritionally inconsistent and lack the digestibility of commercial alternatives (Noor et al., 2021). Consequently, growth performance may suffer, and the pond's carrying capacity may not be fully utilized. Feed formulation research in Bangladesh has yet to produce widely accessible, cost-effective diets that maintain high efficiency while reducing reliance on fishmeal and fish oil. The challenge is to develop feeds that are both economically viable and nutritionally adequate—using sustainable, locally sourced ingredients and targeting the specific dietary requirements of cultured species.

In addition to feed composition, feed management strategies play a pivotal role in enhancing productivity and ensuring environmental sustainability. Overfeeding or poorly timed feeding schedules can lead to the accumulation of uneaten feed, deterioration of water quality, and the proliferation of harmful algal blooms and filamentous vegetation (Tran & Johansen, 2023). These conditions not only compromise fish health but also reduce dissolved oxygen levels, increase disease susceptibility, and ultimately result in economic losses due to mortalities and reduced growth. Conversely, underfeeding leads to poor weight gain and delayed market readiness. The optimal strategy lies in achieving a balance between nutritional intake, water quality, and economic output (Das et al., 2022).

In this context, feed restriction techniques have gained attention as a method to improve feeding efficiency and reduce input costs. These strategies involve either reducing the daily feed allowance or decreasing feeding frequency, with the goal of triggering a physiological response known as compensatory growth (CG)—a phase of accelerated growth following a temporary period of feed deprivation (Assis et al., 2020). CG enables fish to recover lost growth, often achieving body weights similar to continuously fed individuals, while consuming less feed overall. This mechanism has been observed in several species, including tilapia and salmonids, and is associated with improved FCR and lower feed-related expenditures (Hassan et al., 2021). However, the long-term ecological effects of this strategy require careful consideration. Increased excretion of nitrogen and phosphorus during refeeding phases can contribute to eutrophication, while metabolic fluctuations may lead to immunosuppression and increased vulnerability to disease. Furthermore, inconsistencies in growth responses can result in uneven fish sizes and affect market value. The nature of CG can vary by species and severity of restriction, ranging from no compensation to overcompensation (Xavier et al., 2023).

The potential of commercial grower (CG) feeds in aquaculture is well documented. However, no comprehensive studies have evaluated their use in carp polyculture systems. This is especially true for systems that combine factory-made and farm-made feeds. The lack of such studies represents a major research gap, particularly in countries like Bangladesh. Climate change, drought, and economic constraints make low-cost feeding strategies increasingly necessary. Smallholder farmers in drought-prone areas are highly vulnerable. They face frequent feed price fluctuations and unstable input availability. For these farmers, adaptive feed management is vital to maintain production and protect their livelihoods. To address this gap, the present study was conducted. It aimed to evaluate the biological performance, environmental impact, and economic viability of different feeding strategies for carp fattening. The study was carried out in semi-intensive polyculture ponds. Three treatments were investigated: T1, representing 100% commercial feed; T2, combining 70% commercial feed with 30% homemade feed; and T3, which used the same feed composition as T2 but introduced a one-day weekly feed restriction. These treatments were selected based on their potential to maintain fish growth and pond health while reducing feed costs. The objectives of this study were to: (i) compare the effects of the three feeding regimes on growth performance, feed conversion ratio (FCR), and yield of carp; (ii) assess whether these feeding strategies affect water quality and plankton density, as indicators of pond ecosystem stability; and (iii) evaluate the cost-effectiveness and profitability of each treatment for small-scale farmers. Based on previous research on CG and partial feed substitution, it was hypothesized that the combination of 70% commercial feed and 30% homemade feed with one-day weekly feed restriction (T3) would yield comparable or superior growth and economic returns relative to full commercial feeding (T1), without compromising water quality or pond ecology.

2. Materials and methods

2.1. Study area and duration

The present experiment was conducted for a period of 180 days from July to December 2020 in ponds located under Paba Upazila (a sub-district) of Rajshahi district, northwest Bangladesh (Fig. 1). Ponds were located in areas devoid of any industrial and household activities which reduced the possibility of pond water contamination with the pollutants. In accordance with Good Aquaculture Practices (GAP), pond sites were selected in non-polluted areas, and embankments were heightened to prevent wastewater runoff during flooding. Ponds were equipped with inlet and outlet channels for effective water drainage, and bunds were reinforced to offer protection against seasonal flooding. These measures ensured consistent hygienic and biosecure conditions across all experimental units.

2.2. Formulation and proximate composition analysis of feed

In this study, two types of feed were used: (i) a commercially manufactured pelleted feed and (ii) a hand-formulated (homemade) feed developed using locally available ingredients. These feeding strategies were selected to evaluate both the biological performance and economic feasibility of partial feed substitution under semi-intensive pond aquaculture conditions, particularly in drought-prone areas of Bangladesh where feed cost is a critical constraint for smallholders. The commercial feed (Growel Carpmax, Growel Feeds) was used in Treatment 1 (T1) at a full feeding rate. According to the manufacturer's label, its proximate composition included 24.96% protein, 6.20% crude lipid, 7.99% crude fiber, 6.25% ash, and 13.25% moisture, with a calculated gross energy (GE) of 15.23 kJ/g. For the homemade feed, used in Treatments 2 and 3, we followed a structured formulation using fish meal, wheat bran, rice bran, mustard oil cake, vitamin-mineral premix, salt, and binder (Table 1). The formulation approach was adapted from previous research highlighting cost-effective use of locally available materials for carp feed (Giri, 2024; Shipton, 2021). The substitution of commercial feed with homemade feed in T2 was carried out on a weight basis, maintaining a consistent feeding volume but varying cost and nutrient source. In T3, the same homemade-commercial feed mix as in T2 was fed six days per week, with one day of feeding withheld weekly (feed restriction), to simulate a low-cost strategy relevant for small-scale aquaculture systems. This regime is aligned with previous studies demonstrating that short-term feed deprivation does not compromise growth performance and may improve feed efficiency. The hand-formulated feed was produced by thoroughly mixing all dry ingredients and adding water to achieve a dough-like consistency, following standard feed production methods with minor modifications (Fregene et al., 2024). The mixture was then passed through a pelletizer using a 3 mm die, sun-dried for 24 h, and stored at 20 °C prior to feeding. The production cost of the homemade diet was 25.00 BDT/kg,

Fig. 1. Location of the study area is indicated with a dot circle at Paba upazila of Rajshahi district, Bangladesh (modified from a Google map).

Table 1
Ingredients, production cost and proximate composition of prepared diets.

Ingredients	g/kg	Proximate composition	%	Trace elements	Feed types	
					Commercial	Homemade
Fish meal	200	Moisture	13.25	As	1.12 ± 0.03	0.98 ± 0.05
Wheat bran	250	Protein	24.96	Cd	0.22 ± 0.03	0.17 ± 0.04
Rice bran	300	Lipid	6.20	Cr	0.30 ± 0.06	0.20 ± 0.03
Master oil cake	180	Ash	6.25	Pb	0.38 ± 0.04	0.25 ± 0.03
Vitamin & minerals[a]	20.00	Fiber	7.99			
Salt	50.00	NFE	54.61			
Binder	50.00	GE (kJ/g)	15.23			
Production cost (BDT/kg)[b]	25.00					

[a] Feed production cost was estimated during 2020. NFE (Nitrogen free extract) = 100 – (% protein + % lipid + % ash + % fiber), GE = Gross energy content.
[b] Vitamin premix (mg/kg of premix): vitamin A-156000 IU, vitamin D3-31200 IU, vitamin E−299, vitamin K3-26, vitamin B1-32.5, vitamin B2-65, vitamin B6-520, vitamin B12–0.16, Nicotinic Acid-520, Folic Acid-10.4, Copper-130, Iodine-5.2, Manganese-780 and Selenium-1.95. Premix was supplied by Reneta Animal Health Pharma Co. Ltd. Bangladesh. Acceptable limit of As, Cd, Cr and Pb is 0.01, 0.05, 0.01 and 0.30 ppm (Alam & Haque, 2021).

approximately 15% lower than the commercial equivalent. To ensure nutritional comparability and safety, the homemade feed underwent proximate composition analysis following AOAC (2016) protocols: crude protein was measured using the Kjeldahl method (JEQ-16B, India), lipid by Soxhlet extraction (LABORATE LT-SOXA001, India), ash via incineration at 550 °C in a muffle furnace (SH-FU-5MG, SH Scientific Korea), fiber via acid and alkali digestion (Foss Fibertec™ 2010), and gross energy via bomb calorimetry (Leco AC-350, USA). Moisture content was determined at both 70 °C and 105 °C using an oven dryer. Nitrogen-free extract (NFE) was calculated by subtracting the total of all measured components from 100%. The proximate composition of the homemade feed was similar to the commercial product, supporting its nutritional adequacy: 24.96% protein, 6.20% lipid, 7.99% fiber, 6.25% ash, and 54.61% NFE, with gross energy of 15.23 kJ/g (Table 1). This equivalence in energy and nutrient levels ensured the validity of performance comparisons across treatments. In addition, both commercial and homemade feeds were analyzed for trace heavy metals—arsenic (As), cadmium (Cd), chromium (Cr), and lead (Pb)—to ensure compliance with aquaculture food safety standards. For this, 3 g of each feed sample was digested using 5 mL HNO_3 (65%) and 1 mL H_2O_2 (30%) in microwave digestion tubes. Digests were filtered using 0.45 μm Whatman no. 42 paper and analyzed using Flame Atomic Absorption Spectrometry (FAAS) (Shimadzu AA-6800). The results confirmed that all metal concentrations were within acceptable safety limits for aquafeed (Alam & Haque, 2021), with lower levels generally observed in the homemade diet. All ingredient proportions, proximate compositions, and trace element contents of both feed types are detailed in Table 1.

2.3. Experimental design

The experiment was designed to assess the effects of different feeding strategies on the growth performance and economic viability of carp fattening in semi-intensive pond systems. A total of nine ponds were used, with three treatments (T1, T2, and T3) each replicated three times in a randomized complete block design. Each pond had an area of approximately 1.4 ha and an average depth ranging from 1.69 to 1.72 m, with specific pond measurements provided in Table 2. The duration of the study was 180 days, conducted from July to December 2020. Three feeding regimes were evaluated. In T1 (control), fish were fed daily with 100% factory-formulated commercial feed. In T2, 30% of the commercial feed (by weight) was replaced with hand-formulated homemade feed, maintaining a daily feeding schedule. In T3, the same feed composition as T2 (70% commercial and 30% homemade feed) was used, but with a one-day feeding restriction per week, effectively reducing the feeding frequency to six days per week. The selection of the 70:30 ratio in T2 and T3 was based on a combination of published studies and practical field considerations. Prior research has indicated that partial replacement of commercial feed with locally available feed ingredients ranging from 20% to 40% can yield satisfactory growth outcomes while significantly reducing feed costs in carp and tilapia systems (Biswas et al., 2022; Hossain et al., 2020). In addition, preliminary on-farm trials conducted in the region under informal farmer-led initiatives showed that a 30% replacement level strikes a balance between cost-effectiveness and nutrient adequacy without negatively affecting feed acceptability or growth rates. This ratio was therefore selected as a practical compromise to reflect real-world smallholder scenarios while maintaining scientific comparability across treatments.

Each pond was stocked with a polyculture of five carp species: two Indian major carps—*Gibelion catla* (catla) and *Labeo rohita* (rohu); and three exotic carps—*Hypophthalmichthys molitrix* (silver carp), *Cirrhinus cirrhosus* (mrigal), and *Cyprinus carpio* var. *specularis* (mirror carp). The stocking density was 2470 fish per hectare, and the species composition followed a 40:30:30 ratio representing surface, column, and bottom feeders respectively. The total number of fish stocked per pond ranged from ~3392 to 3484 individuals across treatments, as shown in Table 2. Fish fry were sourced from both wild and hatchery origins to simulate common aquaculture practices in the region. Wild fry of *G. catla* and *L. rohita* were collected by professional seed collectors from the Padma River in Rajshahi, while hatchery-bred seeds of the remaining species were obtained from the Rajshahi Fish Seed Multiplication Farm, a government-registered hatchery known for standardized breeding protocols at Bornali Mor under Rajshahi City Corporation, which follows standardized induced breeding protocols and seed quality monitoring practices. All fish underwent standard acclimatization and disinfection protocols before stocking to ensure a healthy baseline across all treatments. This detailed setup aims to ensure replicability and transparency in the experimental protocol.

Table 2
Layout of the experiment.

Parameters	T_1	T_2	T_3
Pond area (ha)	1.41 ± 0.03	1.37 ± 0.05	1.41 ± 0.06
Pond depth (m)	1.69 ± 0.04	1.71 ± 0.03	1.72 ± 0.03
Stocked carps (nos./pond)	3474.67 ± 75.39	3392.00 ± 126.76	3483.00 ± 150.34
Feeding practice	Regular feeding with 100% factory feed	Regular feeding with 70% factory and 30% homemade feed	One day feeding restriction per week with 70% factory and 30% homemade feed

Note: Drugs and chemicals as disinfectants, antibiotics, pesticides, probiotics and feed additives were not used in any treatment.

2.4. Pond preparation, stocking and feeding strategy

Prior to the commencement of the experiment, all ponds were thoroughly cleaned, and unwanted vegetation and predatory fish were eliminated through repeated netting. To condition the pond environment, liming was performed for seven consecutive days at a basal dose of 250 kg/ha, followed by a maintenance dose of 60 kg/ha/week. This was complemented with fertilization using urea (40 kg/ha) and triple superphosphate (TSP, 40 kg/ha) to enhance the productivity of natural plankton as a supplemental food source. All ponds were supplied with groundwater and maintained at a depth of approximately 2.0 m throughout the 180-day culture period. The ponds were then stocked with both healthy wild-sourced and hatchery-produced carp seeds that had undergone overwintering. Wild fingerlings of *Gibelion catla* and *Labeo rohita* were collected from the Padma River in Rajshahi District by licensed professional seed collectors. Meanwhile, hatchery-bred seeds of *Hypophthalmichthys molitrix*, *Cirrhinus cirrhosus*, and *Cyprinus carpio* var. *specularis* were sourced from the Rajshahi Fish Seed Multiplication Farm, Bangladesh. The initial average body weights were 426 g (*G. catla*), 358 g (*H. molitrix*), 325 g (*L. rohita*), 334 g (*C. cirrhosus*), and 340 g (*C. carpio* var. *specularis*). Prior to stocking, all fingerlings were disinfected using a salt bath at 30 g/L for 25–30 min to eliminate potential pathogens. Post-stocking, additional pond fertilization was carried out on alternate months using 30 kg urea and 30 kg TSP/ha to maintain primary productivity. Monthly applications of lime (120 kg/ha) and salt were used to maintain optimal pond hygiene. To minimize external threats, such as predation by birds, surface netting was installed over the ponds. Fish were fed twice daily with their respective feed treatments based on percentage of body weight, following a gradually decreasing feeding rate schedule throughout the 6-month grow-out period. The feeding rate was set at 6% body weight for the first 4 months, then reduced to 4% in the fifth month and 2% in the final month. This schedule is summarized below in Table 3.

The rationale for implementing a progressively decreasing feeding rate—contrary to conventional trials where feeding often increases with fish growth—was based on two key factors. First, as fish grow larger, their metabolic rate per unit body weight declines, resulting in lower relative feed demand. Second, feeding rates were reduced to minimize excessive feed input that could lead to uneaten feed accumulation, thereby increasing water pollution and lowering water quality. This approach aligns with studies suggesting that oversized feeding rates reduce nutrient absorption efficiency and exacerbate waste production (Hossain et al., 2022; Kim et al., 2021; Okorie et al., 2012). By adjusting the feeding rates according to fish size and pond carrying capacity, the strategy helped optimize feed utilization efficiency while reducing production costs and environmental risks.

Table 3
Monthly feeding rate by body weight.

Culture Month	Feeding Rate (% of Body Weight)
Month 1–4	6%
Month 5	4%
Month 6	2%

2.5. Water quality parameters and plankton analysis

Water quality parameters were monitored monthly from 9:00 a.m. to 10:00 a.m. A thermometer was used for the measurement of water temperature and a secchi disc for water transparency (cm). Alkalinity (mg/L) and ammonia-nitrogen (NH_3-N) (mg/L) were determined with the help of a HACH kit (FF2, USA). Dissolved oxygen (mg/L) and pH were determined by a multimeter (HQ 40 D, HACH, USA). For the qualitative and quantitative analysis of plankton, water samples were collected from the ponds in the required amount. Collected samples were preserved with 10% formaldehyde, of which 2–3 drops were transferred onto a glass slide. Planktons were identified microscopically using a phase-contrast microscope (Olympus, Japan) at 100 to 400 with bright field and phase contrast illumination on living materials and on samples preserved with formaldehyde following the keys of Khalil et al. (2022), while cell density was measured by the Sedgewick-Rafter counting chamber (S-R cell) following the method described by Stirling (1985). Counting results were summarized as cells per liter using the following formula: N = (A1000C)/(VFL), where N = no. of plankton cells or units per liter of original water, A = total no. of plankton counted, C = volume of final concentrate of the sample in mL, V = volume of a field in cubic mm, F = no. of fields counted, and L = volume of original water in liter.

2.6. Monitoring of fish growth, feed utilization and yield

Ten individuals of each stocked fishes were caught monthly from each pond with the help of a seine net to study growth performance and to adjust the daily feeding ration. Proper sanitation was maintained during sampling by disinfecting and drying the seine net between the uses. Weight of the sampled fish was measured using a digital balance with an accuracy of 0.1 g. Growth, survival and production performances of fishes were analyzed after Brett & Groves (1979) as follows:

$$\text{Initial weight (g)} = \text{Weight of fish at stock}$$

$$\text{Final weight (g)} = \text{Weight of fish at harvest}$$

$$\text{Daily weight gain (g)} = \text{Mean final weight (g)} - \text{Mean initial weight (g)}$$

$$\text{Specific Growth Rate, SGR (\%, bw / d)} = \frac{L_n\, final\ weight - \boldsymbol{L_n}\ Initial\ weight}{culture\ period} \times 100$$

After the final harvest, the number of fish counted and measured to determine the survival rate (SR), fish yield and feed conversion ratio (FCR) using the following formula:

$$\text{Survival rate (\%)} = \frac{No\ of\ fish\ \text{harvested}}{No\ of\ fish\ \text{stock}} \times 100$$

$$\text{Fish yield (kg/ha)} = \text{Fish biomass at harvest} - \text{Fish biomass at stock}$$

$$\text{FCR} = \frac{Feed\ fed\ gry\ weight}{Fish\ weight\ gain} \times 100$$

2.7. Economic analysis

Total cost of all the variable cost items and fixed cost items were summarized and the final analysis was done to calculate benefit-cost ratio (BCR). The prices were expressed in Bangladesh currency (BDT; 80 BDT = 1 USD in 2020).

The following simple equation was used according to Asaduzzaman et al. (2010) to find out net return: R = I − (FC + VC + Ii)

Where, R = net return, I = income from fish sale, FC = fixed/common costs, VC = variable costs and Ii = interest on inputs.

The benefit-cost ratio was determined as: Benefit-cost ratio (BCR) = Income from fish sale/Total input cost.

2.8. Statistical analysis

All the procured data regarding environmental parameters; fish growth and yield; and economics of carp fattening under different treatments were presented as Mean ± SD. Before conducting the statistical analysis, all the data were checked for normality using Shapiro-Wilk test. The percentages and ratio data were analyzed using arcsine transformed data. Treatment comparison of the data was done by one-way analysis of variance (ANOVA). When a mean effect was significant, the ANOVA was followed by Duncan New Multiple Range Test at 5% level of significance. All analyses were performed using SPSS (Statistical Package for Social Science) version 20.0 (IBM Corporation, Armonk, NY, USA).

3. Results

3.1. Water quality parameters and plankton

Mean water quality values are shown in Table 4. There were no significant differences ($P < 0.05$) in all the water quality parameters among the treatments. Feeding restriction and feed types had a significant effect on phytoplankton density among the treatments (Table 3), whereas the highest numerical cell density was recorded in T_1, followed by T_2 and T_3. However, total zooplankton density did not vary significantly among the treatments.

3.2. Growth performance

Periodic growth performances of fish under different feeds with feeding regimes and the mean growth performance are shown in Table 4. The initial weight of all the stocked fish was uniform during stocking time. After the culture period of 180 days, the final weight of the fishes was measured. Result showed that final weight of the fishes was not significantly ($P < 0.05$) different among the treatments. Therefore, the calculated values of weight gain and SGR were also not significantly different among the treatments. Variation in the survival rate of the fishes was not significant among the treatments and it ranged between 88 and 93%. Feeding restriction and feeding strategy were found to influence the growth parameters of carp species, whereas numerically higher growth performance was recorded for fish regularly fed with 100% factory feed at T_1.

3.3. Feed conversion ratio (FCR)

The feed conversion ratio (FCR) of different treatments is shown in Fig. 2. Significantly lower value of FCR was observed in T_3 (2.79 ± 0.22) compared to T_1 and T_2, whereas, value of FCR between T_1 (3.33 ± 0.19) and T_2 (3.07 ± 0.17) was not significant ($P < 0.05$). Feeding restriction for 1-day per week reduced the amount of feed given in T_3, while increasing the feeding efficiency.

Table 4
Environmental parameters under different treatments of feed and feeding regimes.

Parameters	T_1	T_2	T_3	F-value	P-value
Temperature (°C)	30.90 ± 0.03^a	31.06 ± 0.20^a	31.21 ± 0.05^a	0.54	0.61
Transparency (cm)	25.66 ± 0.25^a	26.94 ± 0.24^a	26.44 ± 0.48^a	1.30	0.34
DO (mg/l)	6.73 ± 0.06^a	6.72 ± 0.14^a	6.98 ± 0.06^a	2.29	0.21
pH	7.78 ± 0.10^a	7.82 ± 0.03^a	7.95 ± 0.12^a	0.81	0.49
Alkalinity (mg/l)	155.83 ± 4.09^a	152.11 ± 3.80^a	153.00 ± 2.94^a	0.28	0.76
NH_3-N (mg/l)	0.05 ± 0.00^a	0.04 ± 0.00^a	0.03 ± 0.00^a	3.59	0.09
Total phytoplankton ($\times 10^5$ cells/l)	94.86 ± 0.86^a	39.50 ± 2.00^b	36.68 ± 0.99^b	1456.55	0.04
Total zooplankton ($\times 10^3$ cells/l)	4.14 ± 0.32	3.88 ± 0.67	4.03 ± 0.98	768.55	0.45

Values in the same row with different superscript differ significantly ($P < 0.05$). T_1 Regular feeding with 100% factory feed; T_2 Regular feeding with 70% factory and 30% homemade feed and T_3 One day feeding restriction per week with 70% factory and 30% homemade feed.

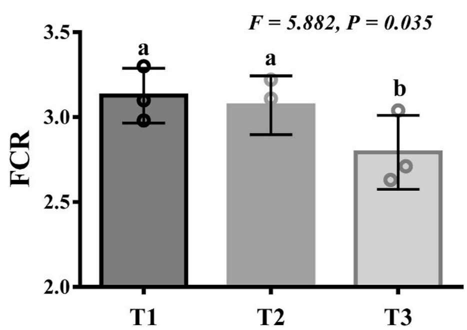

Fig. 2. Feed conversion ratio (FCR) at different treatments of feed and feeding regimes. Bars with the same superscripts indicate insignificant difference among the treatments ($P < 0.05$). T_1 Regular feeding with 100% factory feed; T_2 Regular feeding with 70% factory and 30% homemade feed and T_3 One day feeding restriction per week with 70% factory and 30% homemade feed. Bars with different lowercase letters indicate statistically significant differences among treatments ($P < 0.05$).

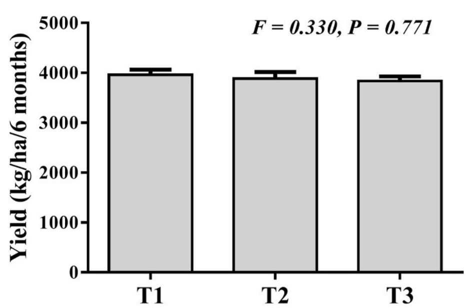

Fig. 3. Fish yield (kg/ha/6 months) at different treatments of feed and feeding regimes. Bars with the same superscripts indicate insignificant difference among the treatments ($P < 0.05$). T_1 Regular feeding with 100% factory feed; T_2 Regular feeding with 70% factory and 30% homemade feed and T_3 One day feeding restriction per week with 70% factory and 30% homemade feed.

3.4. Fish yield

The final yield of fish reared at different treatments of feed and feeding regimes is shown in Fig. 3. The yield of all the studied fish species responded insignificantly ($P < 0.05$) among the treatments. As per the yield of *G. catla, a* numerically higher value was obtained from the fish fed with 100% factory feed with regular feeding in T_1. While a higher yield of *H. molitrix* was observed in T_3. The yield of *L. rohita* ranged between 867.76 ± 41.23 (T_3) and 922.71 ± 43.73 kg/ha/6 months (T_1). Similarly, the highest yield of *C. cirrhosus* was recorded in T_1 (533.01 ± 7.26 kg/ha/6 months) and the lowest at T_3 (512.58 ± 4.79 kg/ha/6 months). However, an insignificant but higher yield of *C. carpio* was found in T_2 (296.21 ± 11.60 kg/ha/6 months), whereas the fishes were fed with 70% factory feed and 30% homemade feed and one day of feeding restriction per week. Moreover, the combined yield of all the fish species was insignificant ($P < 0.05$), whereas a numerically higher yield was obtained in T_1 (3960.84 ± 104.89 kg/ha/6 months), followed by T_2 (3886.27 ± 128.58 kg/ha/6 months) and T_3 (3834.95 ± 91.48 kg/ha/6 months). Therefore, fish yield in T_1 was 1.88 and 3.17% higher than T_2 and T_3, respectively.

3.5. Economics

The economic output of carp fattening under different feeds and feeding regimes is shown in Table 5. Among the variable costs, feed cost differed significantly ($P < 0.05$) among the treatments; whereas the higher feed cost was recorded in T_1 followed by T_2 and T_3. Therefore, total feed cost in T_3 was 26.63 and 18.55% lower compared to T_1 and T_2, respectively. Among the fixed cost items, lease value, water used, lime, fertilizer, labour and harvest costs were kept constant for all the treatments to reduce bias. However, the total cost of the experiment varied significantly ($P < 0.05$) among the treatments. Significantly ($P < 0.05$) higher total cost was recorded in T_1 followed by T_2 and T_3. Substitution of 30% commercial feed in T_2 caused 5.71% reduction in total cost compared to T_1. Following a 1-day feeding restriction in T_3, the total cost was 10.45% lower in T_3 compared to T_2. Again, practising 1-day of feeding restriction per week in T_3 along with 30% substitution of commercial feed caused a 15.57% lower total cost compared to T_1. During the study period, feed cost was the major cost involving the area, accounting for 57.73, 55.15 and 44.16% of the total cost. The difference in total return among the treatments was insignificant ($P < 0.05$), however, it was significant for net benefit. Net benefit was significantly ($P < 0.05$) higher in T_3, followed by T_2 and T_1. Therefore, total profit in T_3 was 19.49 and 28.89% higher than T_2 and T_1, respectively (see Table 6).

4. Discussion

The water quality parameters in the current study were not affected by the types of diets administered. No significant differences were observed among treatments for temperature, transparency, dissolved oxygen (DO), pH, alkalinity, or ammonia-nitrogen (NH_3-N). These parameters remained within the acceptable range for aquaculture systems, as established in the literature and were consistent with values reported by Hossain et al. (2020) and Minabi et al. (2020). The uniformity in water quality parameters may be partially attributed to the consistent design, size, and depth of the experimental ponds, as well as standardized management practices applied across treatments. However, while this level of control strengthens internal validity, it is important to acknowledge that such uniform conditions may not fully capture the variability typically present in smallholder pond systems in Bangladesh. Heterogeneous farm conditions such as irregular pond geometry, inconsistent water exchange, and variable feeding practices could influence nutrient cycling and environmental dynamics differently. These factors warrant further investigation to better understand how scalable and adaptable the current feeding regimes are under diverse field conditions.

Table 5
Growth performance of fishes under different treatments of feed and feeding regimes.

Species	Treatment	Initial weight (g)	Final weight (g)	Weight gain (g)	SGR (%, bw/d)	Survival rate (%)	Yield (kg/ha/6 months)
G. catla	T_1	419.66 ± 2.02^a	2876.33 ± 67.53^a	2456.66 ± 66.62^a	1.06 ± 0.01^a	92.03 ± 1.19^a	1651.61 ± 67.99^a
	T_2	431.33 ± 4.17^a	2867.00 ± 6.45^a	2435.66 ± 63.53^a	1.05 ± 0.02^a	91.54 ± 0.59^a	1625.15 ± 45.70^a
	T_3	427.00 ± 6.11^a	2820.66 ± 46.49^a	2393.66 ± 46.20a	1.04 ± 0.01^a	91.67 ± 1.09^a	1600.50 ± 54.43^a
	F	1.77	0.25	0.29	0.66	0.06	0.20
	P	0.24	0.78	0.75	0.54	0.93	0.82
H. molitrix	T_1	359.00 ± 3.78^a	2828.66 ± 26.20^a	2479.66 ± 29.80^a	1.16 ± 0.01^a	91.90 ± 0.40^a	555.88 ± 6.21^a
	T_2	356.00 ± 5.56^a	2807.33 ± 54.89^a	2451.33 ± 56.26^a	1.14 ± 0.02^a	90.55 ± 1.81^a	540.33 ± 23.71^a
	T_3	358.33 ± 1.20^a	2802.00 ± 8.88^a	2443.66 ± 9.59^a	1.14 ± 0.03^a	93.25 ± 1.17^a	556.86 ± 7.31^a
	F	1.51	0.15	0.26	0.89	1.12	0.39
	P	0.29	0.85	0.77	0.45	0.38	0.69
L. rohita	T_1	331.66 ± 7.26^a	1718.00 ± 47.84^a	1386.33 ± 54.97^a	0.91 ± 0.02^a	91.76 ± 0.97^a	922.71 ± 43.73^a
	T_2	323.33 ± 3.38^a	1687.00 ± 43.84^a	1363.66 ± 42.11^a	0.92 ± 0.01^a	91.04 ± 0.86^a	899.10 ± 38.69^a
	T_3	320.33 ± 4.48^a	1641.33 ± 39.95^a	1321.00 ± 43.82^a	0.90 ± 0.02^a	90.82 ± 1.28^a	867.76 ± 41.23^a
	F	1.22	0.76	0.49	0.06	0.21	0.44
	P	0.35	0.50	0.63	0.94	0.81	0.66
C. cirrhosus	T_1	331.33 ± 2.40^a	1595.33 ± 31.68^a	1254.00 ± 34.04^a	0.85 ± 0.01^a	89.06 ± 1.01^a	533.01 ± 7.26^a
	T_2	337.00 ± 4.04^a	1526.00 ± 37.43^a	1237.00 ± 34.82^a	0.86 ± 0.01^a	88.93 ± 1.13^a	525.45 ± 24.10^a
	T_3	334.66 ± 5.17^a	1526.00 ± 12.66^a	1191.33 ± 10.49^a	0.84 ± 0.01^a	89.94 ± 1.18^a	512.58 ± 4.79^a
	F	0.70	1.47	1.26	0.47	0.24	1.48
	P	0.53	0.30	0.34	0.64	0.79	0.63
C. carpio	T_1	334.66 ± 3.28^a	1721.66 ± 53.73^a	1387.00 ± 55.24^a	0.91 ± 0.02^a	89.47 ± 1.68^a	257.62 ± 1045^a
	T_2	340.66 ± 5.98^a	1694.66 ± 37.48^a	1354.00 ± 32.74^a	0.89 ± 0.01^a	90.82 ± 1.05^a	296.21 ± 11.60^a
	T_3	344.66 ± 4.80^a	1664.66 ± 41.55^a	1320.00 ± 45.76^a	0.87 ± 0.02^a	92.98 ± 0.95^a	257.24 ± 11.81^a
	F	1.10	0.40	0.54	1.02	2.30	1.88
	P	0.39	0.68	0.60	0.41	0.18	0.99

Values in the same row with different superscript differ significantly ($P < 0.05$). T_1 Regular feeding with 100% factory feed; T_2 Regular feeding with 70% factory and 30% homemade feed and T_3 One day feeding restriction per week with 70% factory and 30% homemade feed.

Table 6
Economics of carp fattening in pond (1 ha) under different treatments of feed and feeding regimes.

Items	Treatments			F-value	P-value
	T_1	T_2	T_3		
Variable cost (BDT/ha)					
Seed	110026.97 ± 539.38^a	110177.64 ± 718.53^a	109466.28 ± 834.63^a	0.28	0.76
Feed	477043.00 ± 708.53^a	429672.65 ± 872.80^b	309970.50 ± 92.88^c	972.93	0.00
Fixed cost (BDT/ha)					
Lease value	125000.00 ± 0.00	125000.00 ± 0.00	125000.00 ± 0.00	–	–
Water (pump)	11000.00 ± 0.00	11000.00 ± 0.00	11000.00 ± 0.00	–	–
Lime	14300 ± 0.00	14300 ± 0.00	14300 ± 0.00	–	–
Fertilizer	18420.00 ± 0.00	18420.00 ± 0.00	18420.00 ± 0.00	–	–
Labour	54500.00 ± 0.00	54500.00 ± 0.00	54500.00 ± 0.00	–	–
Harvest	16000.00 ± 0.00	16000.00 ± 0.00	16000.00 ± 0.00	–	–
Total cost (BDT/ha)	826289.97 ± 818.33^a	779070.29 ± 1504.59^b	697656.78 ± 783.49^c	352.81	0.00
Total return (BDT/ha)	1064168.72 ± 24603.45^a	1048381.13 ± 2822.28^a	1033175.15 ± 22110.97^a	0.38	0.69
Net benefit (BDT/ha)	237878.75 ± 24508.08^b	269310.84 ± 2733.20^{ab}	334518.37 ± 22652.45^a	3.91	0.04
BCR	1.28 ± 0.03^b	1.35 ± 0.03^b	1.48 ± 0.03^a	9.09	0.01

Values in the same row with different superscript differ significantly ($P < 0.05$). T_1 Regular feeding with 100% factory feed; T_2 Regular feeding with 70% factory and 30% homemade feed and T_3 One day feeding restriction per week with 70% factory and 30% homemade feed.

The growth performance of cultured carp species did not vary significantly among the feeding regimes. Nonetheless, fish fed a complete commercial diet (T1) showed numerically higher weight gain and specific growth rate, indicating the potential benefits of nutritionally balanced commercial feed in maximizing growth. On the other hand, fish in Treatments 2 (T2) and 3 (T3), which included partial substitution with homemade feed, achieved comparable growth outcomes. The slightly reduced growth observed in these treatments may be attributed to variability in ingredient quality, digestibility, or particle size of the homemade diet (Hossain et al., 2024). It is important to emphasize, however, that the primary objective of the study was not solely growth maximization, but rather to assess cost-effectiveness and feed efficiency, especially for low-input systems. Survival rates remained statistically similar across treatments and above critical thresholds, suggesting that all feeding regimes provided sufficient nutrients to support fish health under the prevailing water quality conditions.

Yield performance also did not differ significantly among treatments. The overall biomass production in T1 (3960.84 ± 104.89 kg/ha/6 months) was marginally higher than in T3 (3834.95 ± 91.48 kg/ha/6 months), but these differences were not statistically significant. Yield in aquaculture is influenced by complex interactions among growth rate, survival, feed efficiency, and environmental stability (Boyd et al., 2020; Lall & Dumas, 2022). The similar outcomes across treatments reaffirm that partial substitution and restricted feeding strategies can sustain production levels comparable to full commercial feeding. These yields also exceeded those reported in previous polyculture studies in the region (Khan et al., 2018; Das et al., 2019), further supporting the technical feasibility of the approaches tested.

A key highlight of this study is the significant improvement in feed conversion ratio (FCR) observed in T3, followed by T2 and then T1. The superior FCR in T3 is largely attributed to the one-day-per-week feeding restriction, which reduced total feed input while maintaining acceptable growth and survival. Intermittent feeding strategies like this have been widely reported to induce compensatory feeding responses such as hyperphagia and enhanced nutrient absorption during refeeding, resulting in improved feed utilization (Py et al., 2022). Similar improvements in FCR and feed efficiency under short-term feed restriction have been observed in tilapia (*Oreochromis niloticus*) by Smith et al. (2023) and in rohu (*Labeo rohita*) and common carp (*Cyprinus carpio*) by Thomas et al. (2021). The decision to apply a one-day-per-week restriction was guided by both practical considerations and findings from prior studies, which suggest that mild feed restriction schedules (e.g., skipping one day per week) can improve feed efficiency without inducing growth suppression or behavioral stress (Sabbir et al., 2018; Hossain et al., 2020). Nevertheless, it is important to acknowledge the potential trade-offs associated with this strategy. While no significant differences in survival or observable behavioral stress were recorded in this study, restricted feeding schedules may risk inducing uneven growth rates among individuals due to heightened competition during refeeding, particularly in systems with suboptimal feeding distribution. Chronic stress responses or suppressed immune function could also emerge under prolonged or poorly managed restriction regimes. Although these risks were not apparent in the present trial, they warrant further investigation using physiological stress markers such as cortisol levels or oxidative stress indicators to better assess the long-term welfare implications. In operational contexts, the success of this strategy will also depend on farmers' ability to manage feed distribution effectively during refeeding days, ensuring that smaller or less dominant fish are not chronically underfed. Overall, while T3 shows promise as a cost-effective and feed-efficient strategy, its broader applicability should consider both biological variability and management capacity across smallholder systems.

Economically, the combination of homemade feed and feeding restriction in T3 delivered the most favorable cost-benefit outcome. T2 and T3 achieved 9.93% and 35.02% reductions in feed cost, respectively, compared to T1. These savings were reflected in lower overall production costs (5.71% in T2 and 15.57% in T3) and in the highest cost-benefit ratio in T3. Such results are consistent with the findings of Kaleem and Sabi (2021), who reported that feeding frequency adjustments can reduce operating costs without compromising yield. However, it is critical to note that the cost estimates in this study excluded labor costs associated with homemade feed preparation. This includes manual operations such as ingredient grinding, mixing, pelletizing, sun-drying, and storage. While such labor may be considered unpaid in household systems, its opportunity cost must be acknowledged to realistically assess economic feasibility. Inclusion of labor valuation, especially in wage-based or enterprise-level systems, would provide a more robust comparison of actual feed costs. In addition to labor, price volatility in feed ingredients presents a real-world challenge for smallholder aquaculture. A sensitivity analysis of cost fluctuation scenarios would further enhance the reliability of the economic conclusions. For instance, a 15%–20% increase in fishmeal or oilcake prices could diminish the cost advantage of homemade diets. Therefore, future research should incorporate dynamic feed cost modeling, including least-cost formulation tools and real-time price tracking, to provide adaptive strategies for farmers operating under fluctuating input markets.

To contextualize the performance of the homemade diet used in this study, Table 7 presents a comparative analysis with other recent formulations reported in the literature. The hand-formulated feed used here, composed of fishmeal, rice bran, mustard oil cake, wheat bran, and premix, achieved a competitive protein level (24.96%) and the lowest cost per kg of gain (43.75 BDT/kg in T3) among all compared studies. This performance, coupled with favorable FCR and production cost outcomes, underscores the practicality and cost-efficiency of this feed design (Biswas et al., 2022; Hossain et al., 2020; Kabir et al., 2023). While commercial feeds remain preferable for maximum growth, the homemade alternative offers a compelling advantage for financially constrained farmers seeking to sustain yield while minimizing costs.

Environmental implications of reduced feed input also merit attention. Although direct measurements were not included, it is widely established that reduced feeding lowers nutrient excretion rates particularly nitrogen and phosphorus, thereby minimizing eutrophication risks and sediment nutrient buildup (Boyd et al., 2020). Commercial feeds with higher digestibility in T1 likely led to more rapid nutrient turnover, stimulating phytoplankton productivity as observed. In contrast, the slower nutrient cycling in T2 and T3 could explain the lower phytoplankton density, while zooplankton populations remained stable across treatments. These dynamics align with previous studies (Ahmed et al., 2019) suggesting that primary productivity is more immediately responsive to feed-driven nutrient flux than secondary consumers. To better support sustainability claims, future studies should include nutrient budgeting and excretion analyses to quantify environmental loading more precisely.

5. Conclusion

The present study demonstrated that partial substitution of commercial feed with a nutritionally balanced homemade feed, combined with a one-day-per-week feeding restriction (T3), is a practical and cost-effective strategy for carp fattening in drought-prone regions of Bangladesh. Although growth performance and yield were statistically similar across all treatments, T3 significantly reduced feed costs by 15.57% and achieved the best feed conversion ratio (FCR), making it the most economically efficient option. The observed increase in phytoplankton density in T3 ponds may also suggest enhanced natural productivity, which could complement nutritional intake during restricted feeding periods. Zooplankton densities remained stable, indicating no negative ecological impacts. These results support the adoption of the T3 feeding regime by small-scale farmers, particularly those facing high

Table 7
Comparative summary of homemade carp feeds.

Ingredients	Protein Content (%)	Feeding Regime	Growth Outcome	FCR	Cost/kg Feed (BDT)	Cost/kg Gain (BDT)	Reference
Fish meal, rice bran, mustard oil cake, wheat flour	25	Twice daily, 5% BW	Moderate growth	2.2	28	61.6	Hossain et al. (2020)
Fish meal, rice polish, maize gluten, wheat bran, premix	26.5	Thrice daily, 4% BW	Good growth	2.1	30	63	Biswas et al. (2022)
Soybean meal, rice bran, wheat bran, vitamin-mineral premix	24.8	Twice daily, 3% BW	Moderate growth	2.3	26.5	60.95	Kabir et al. (2023)
Fish meal, rice bran, mustard oil cake, wheat bran, premix, binder	24.96	Twice daily, 3% BW equivalent (partial substitution)	Comparable to commercial feed	1.98	25	49.5	Present Study (T2)
Same as T2 with 1-day feeding restriction	24.96	Twice daily, 3% BW, 6 days/week	Slightly lower than T1 but efficient	1.75	25	43.75	Present Study (T3)

feed costs and limited access to inputs. Extension services should provide training on formulating and applying homemade feeds, while policymakers are encouraged to incentivize such low-input strategies through subsidies, technical support, and inclusion in climate-resilient aquaculture programs. Emphasizing feed efficiency and input cost reduction, rather than biological growth maximization alone, offers a practical pathway to improving profitability and sustainability in smallholder aquaculture systems.

To strengthen the scientific rigor of future feeding trials, it is recommended that newly formulated diets be first evaluated under controlled conditions in laboratory tanks or aquaria. Such environments allow precise regulation of temperature, dissolved oxygen, and other water quality parameters critical to fish growth, thus improving feed assessment prior to pond-scale application. This two-step approach will enhance feed development accuracy and minimize variability from uncontrolled field conditions. For effective dissemination, aquaculture extension services should be mobilized to train farmers on the formulation, preparation, and application of nutritionally adequate homemade feeds. Community-level demonstration programs, technical handbooks, and mobile-based advisory platforms could serve as accessible tools to empower smallholders. Policymakers are also encouraged to support this transition by providing targeted incentives such as subsidies for essential feed ingredients, equipment grants for small-scale pellet production, or inclusion of T3-based models in national climate-resilient aquaculture schemes.

The way forward involves scaling this feeding strategy through inclusive policies, participatory extension programs, and continuous technical validation. Further research is warranted to assess the long-term impacts of intermittent feeding on fish physiology, reproductive performance, stress tolerance, and nutrient loading. In particular, quantifying nitrogen and phosphorus excretion under restricted feeding regimes will strengthen sustainability claims and inform nutrient budgeting for eco-friendly pond management. Adoption of the T3 strategy directly contributes to several Sustainable Development Goals (SDGs), including SDG 1 (No Poverty) through increased farm profitability, SDG 2 (Zero Hunger) via improved food production efficiency, SDG 12 (Responsible Consumption and Production) through reduced input dependency, and SDG 13 (Climate Action) by promoting adaptive aquaculture practices suited to resource-constrained and climate-sensitive regions. By aligning feed innovation with sustainability, this study offers a practical model for enhancing the resilience, productivity, and inclusivity of smallholder aquaculture systems.

CRediT authorship contribution statement

Md Anwar Hossain: Writing – original draft, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Md Akhtar Hossain:** Writing – original draft, Formal analysis, Data curation. **Md Ayenuddin Haque:** Writing – original draft, Methodology, Formal analysis. **Mst Nurjahan Begum:** Writing – review & editing, Methodology, Formal analysis. **Sumaiya Akter:** Writing – review & editing. **Noorashikin Md Noor:** Writing – review & editing, Visualization. **Azlan Abas:** Writing – review & editing, Visualization. **Simon Kumar Das:** Writing – review & editing, Validation.

Data accessibility statement

The data produced during this study has been reported in this paper.

Ethics statement

All experimental protocols involving live animals were reviewed and approved by the Universiti Kebangsaan Malaysia Animal Ethics Committee under protocol code FST/2016/SIMON/27-JULY/763-JULY-2016-MAY-2017 and conducted in accordance with institutional guidelines and relevant national legislation.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author did not use generative AI or AI-assisted technologies in the writing process. All content was prepared, reviewed, and edited solely by the author, who take full responsibility for the integrity and originality of the published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to thank the National Agricultural Technology Program Phase-II, Bangladesh Agricultural Research Council (BARC) for providing funding (NATP 2/BARC/IDA/IFAD/PBRG-037) for this study.

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