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Original Article

Determining overwintering performance and economic viability of monosex tilapia fingerling production in hapa cum cage aquaculture system for Bangladesh's haor fishers

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Abstract
Ensuring a consistent supply of uniformly sized fingerlings for tilapia cage aquaculture in Bangladesh's poses a significant challenge. This study assessed overwintering growth performance and economic viability of monosex tilapia fingerling production in haor waters. Nine hapas, each inside a designated treatment cage, were stocked with T_1 (200), T_2 (250) and T_3 (300) tilapia fry, averaging 1.25±0.25 g, per m³ for 90 days. The most successful treatment continued for two subsequent crops over two years for economic viability assessment. Average final body weight gain was the highest at the lowest stocking density (T_1, 58.86±7.23 g), but the most desirable biomass gain (222 kg cage^{-1}) occurred at medium stocking density (T_2). Beyond biomass gain, T_2 exhibited superior profitability, with 26% and 30% profitability in the second and third crops respectively, over total costs. In conclusion, overwintering tilapia fingerling production in the hapa-cum-cage system at a stocking density of 250 m^{-3} proved more profitable and sustainable than other treatments, offering a viable income-generating option for resource-poor haor fishers.

Keywords: economic viability; growth performance; haor; hapa cum cage aquaculture system; monosex tilapia; overwintering

1 | INTRODUCTION

Since the early 1950s, global aquaculture production has been steadily and dramatically increasing (Lusher *et al.* 2017). This trend is expected to continue into the current millennium, driven by the rising demand for animal protein sources, especially fish products, to meet the needs of the growing population (De Silva 2001). The fulfilment of this demand largely depends on aquaculture making a significant contribution to the global fish markets' quantity and future availability (Merino *et al.* 2012). It is worth noting that Bangladesh is the world's fifth-largest aquaculture producer, accounting for over 2% of global production (FAO 2022). Aquaculture, in Bangladesh, contributes approximately 57% to the inland fish production, producing a total of 2.73 million metric tonnes in 2021–22 (DoF 2023). Furthermore, it serves as a vital pathway for poverty alleviation, social and economic development (Karim 2006; Haque *et al.* 2006; Haque 2007; Belton *et al.* 2011; Little *et al.* 2012). This remarkable production can be attributed to the recent expansion and intensification of pond aquaculture. Among different forms of aquaculture, cage aquaculture has received significant attention for its technical simplicity, ease of feeding, health monitoring and harvesting (Mondal *et al.* 2010). In the context of cage culture, the annual fish production in 2021–22 was 5.02 thousand metric tonnes with the average annual growth rate of 9.49% over the last five years (DoF 2023). Successful cage aquaculture relies on several factors, including proper cage net quality, seed quality, stocking density, feeding, water management, cage maintenance and harvesting (Beveridge 2004). The availability of tilapia fry and/or fingerlings serves as a key indicator for sustainable cage culture (Belton *et al.* 2011), since the lack of tilapia broods for breeding early in the carp seed production season is the major constraints to tilapia seed production (Dan and Little 2000). Typically, tilapia starts breeding in between March and April when water temperatures remain above 20°C (Dan and Little 2000). This made tilapia fingerlings available in June – July, during when farmers have usually stocked carps (Dan and Little 2001). Overwintering of late-spawned tilapia fry to make large-sized fingerlings available in the grow-out season can be considered a possible option (Crab *et al.* 2009).

During overwintering, fingerlings are stocked with high stocking density and are fed just enough to maintain good health conditions (Cruz and Ridha 1994). The techniques for producing tilapia fingerlings from fry through overwintering are simple and applicable to various culture mediums, requiring minimal input from farmers, making it accessible and beneficial (Little *et al.* 2003). This method exhibits a broad tolerance range concerning diseases and environmental stress (Hossain *et al.* 2005). Dan and Little (2001) reported overwintering of tilapia fingerlings spawned the previous year as a solution for getting tilapia fingerling at appropriate time of stocking in the next year in northern Vietnam. Overwintering of tilapia broodstock and fry has been conducted successfully using costly heating facilities (Behrends *et al.* 1990), groundwater (Cruz and Ridha 1994) and greenhouses insulated with plastic sheet covers (Jiazhao 1991).

The mass production of tilapia seed has gained popularity through the use of 'hapas' (fine-meshed nylon net enclosures installed inside larger cages) at different intensity levels (Guerrero and Garcia 1983; Hughes and Behrends 1983; Mair and Little 1991; Little *et al.* 1993; Beveridge 2004; Siddik *et al.* 2007). The 'hapas' system is also applicable for producing high-quality tilapia fingerlings of the same age and size (Dan and Little 2000; Little *et al.* 2003). However, successful implementation of this culture technique in resource-poor households requires active participation and proper training, as emphasised by Fleisher *et al.* (2002) and Cramb *et al.* (2004).

Haors, a complex aquatic environment with rivers, streams, canals, flooded plains and interconnected beels (wetlands) (Hussain and Salam 2007), covers a quarter of Northeastern Bangladesh (Pandit *et al.* 2015). Around 0.4 million poor fishermen of these regions use haor resources to sustenance their livelihood (DoF 2023). Traditionally, fishers of the haor region collect fish fry from natural water bodies like rivers and wetlands (Rahman 2008) and from long-distanced fish hatcheries (Islam and Begum 2019) for aquaculture purpose. In most cases, fishers directly stocked the collected fry in their cages or culture mediums and only limited fishers who have small ponds stocked the collected fry to small ponds or enclosures where they are reared until they reach a suitable size for release or further growth. However, the availability of naturally occurring fish fry often reported unpredictable and insufficient to meet the demand for aquaculture of that region (Kunda *et al.* 2014). Moreover, the reliance on natural fry collection can pose a threat to wild fish populations, potentially leading to ecological imbalances (Debnath *et al.* 2020). On the other hand, the quality and health of collected fry from hatcheries are often not guaranteed, leading to issues related to high mortality and poor growth rates (Islam and Begum 2019). Therefore, fry rearing in cages is becoming a popular activity day by day to haor fishers (DoF 2023). Moreover, Siddik *et al.* (2014) reported that the haor region of Bangladesh is confronted with a prolonged winter period. Therefore, over-wintering fingerling production can be an important solution to meet the timely supply of fingerling and to generate alternate income through cage farming activity of that part. Few literatures are available on producing tilapia fingerling in the haor region (Kunda *et al.* 2014; Uddin *et al.* 2016; Islam and Begum 2019), however, no information is available on the production of overwintered monosex tilapia fingerlings in hapa cum cages in haor waters.

In this research, we formulated a hypothesis suggesting that overwintering monosex tilapia fry in a hapa cum cage aquaculture system in haor areas could represent the most suitable and cost-effective nursing system. This system has the potential to be replicated for sustainable cage aquaculture in Bangladesh. The objective of our research was to investigate overwintering performance of monosex tilapia fingerling production in terms of technical and economic viability to empower resource-poor fisher's community. We aimed to ensure an uninterrupted early supply of stock-able fingerlings, approximately weighing between 30 and 70 g, in the hapa cum cage aquaculture setup within the haor areas. We wanted to validate the initial positive outcome, if any, for two subsequent crops. This research is particularly crucial as only a limited number of studies have explored the technical and economic viability of overwintering outputs in Bangladesh.

2 | METHODOLOGY

This study conducted in the haor region of Bangladesh. A collaborative approach was taken involving local fisher communities. The selected households were actively trained by the research team to implement a three-month-long research initiative that spanned subsequent two crops over two years. The study focused on training these communities in various aquaculture practices, including the installation of hapas inside cages, stocking, feeding and marketing of overwintered tilapia fingerlings. The research team provided hands-on guidance and supervision throughout the process, aiming to enhance the community's knowledge and skills in sustainable hapa cum cage aquaculture. This participatory approach not only evaluated the feasibility of the hapas cum cage aquaculture but also empowered resource-poor fisher communities, contributing to socio-economic improvements in the region.

2.1 Site and community selection

This study was conducted at two haor-based villages (Sutarpara and Changnoagaon) of Karimganj sub-district (upazila) in the Kishoreganj District of Bangladesh (24°27′40.97″N 90°58′16.61″W; Figure 1). The selection of this region was driven by the presence of resource-poor fisher communities, favourable geographical conditions suitable for cage aquaculture and specific development challenges, such as a lack of knowledge. Additionally, there was a preference for developing tilapia fry overwintering technology for early stock-able size fingerling production, aimed at promoting aquaculture and enhancing livelihood options.

Out of the 80 households in the resource-poor communities of the studied villages, nine households were chosen for the three-month-long (November 2015 – January 2016) research, involving repeated crops over next two years (November 2016 – January 2017 and November 2017 – January 2018). The research was implemented directly by these community households.

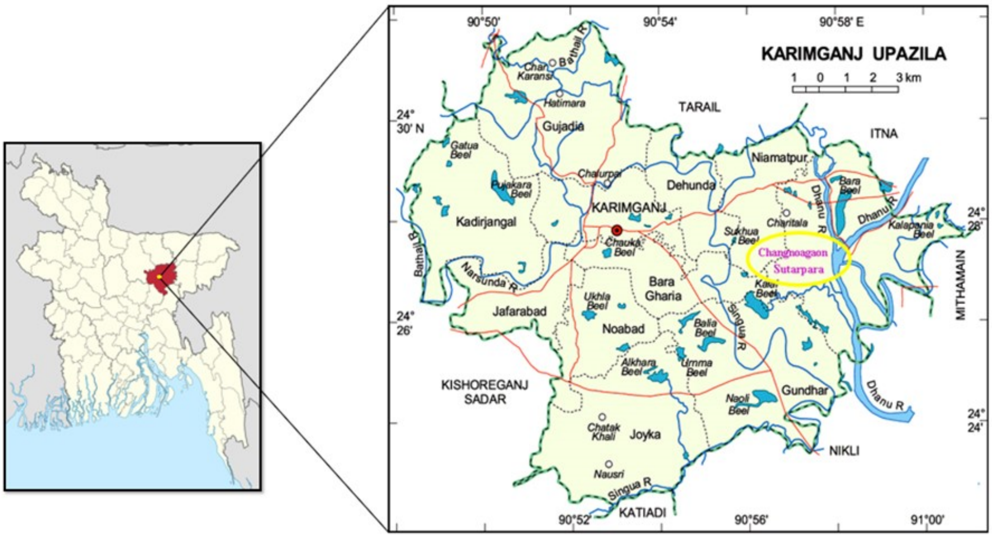

FIGURE 1 Location of the studied hapas cum cage aquaculture villages (yellow circled) of Karimganj Upazila under Kishoreganj district, Bangladesh (Source: Wikimapia).

2.2 Stockable size of tilapia fry and fishers' training

In the haor region, small-sized tilapia fry often experience high mortality during transportation from distant fish hatcheries to reservoirs. A similar observation was made by Karnatak and Kumar (2014), who noted significant fingerling mortality during transportation to reservoir for stocking. To address this challenge, tilapia fry sourced from a hatchery were reared in a small pond near the study area, allowing them to grow to a size of 1 – 1.5 g since Dan and Little (2000) and Kamel *et al.* (2008) found 54% (*O. niloticus*) and 32% (*O. aureus*) survival rates while they overwintered 1.0 g and 0.4 g tilapia fry respectively, in hapas-in-ponds systems. This approach aimed to improve the survival rate of the stocked tilapia fry which was a crucial aspect of a program aimed at enhancing the capacity of resource-poor community fishers in the haor region. Given that these fishers primarily engage in capture fishing, their knowledge about aquaculture is limited. Therefore, a comprehensive training program, focusing on the installation of hapas inside the cages, stocking, feeding, sampling, and marketing of fingerlings for overwintering in hapas cum cage aquaculture activities in haor waters, was provided to the fishers to increase their knowledge and skills.

2.3 Experimental design

The hapas utilised in this study measured 18×9×3.5 ft³, with a mesh size of 0.2 cm, whereas the cages were sized 20×10×6 ft³ with a mesh size of 1 cm. These hapas were installed inside the cages, accommodating varying water depths ranging from 1 – 2 feet during low tide to high tide. Nine hapas were placed in nine cages in a single row. Nine hapas were divided into three treatments each with triplicate and tilapia fry were stocked separately and randomly into triplicate at a density of 200 (T_1), 250 (T_2) and 300 (T_3) per m³ for 90 days. Each hapa was used for only one crop due to its tendency to develop large pores at the end of the trial, making it unsuitable for subsequent use. Otherwise, using hapas for subsequent crops might result in fry escaping through the larger pores created during the first crop.

2.4 Feeding strategies

The tilapia fry with an average weight of 1.25 ± 0.25 g used in the study were primarily sourced from a commercial fish hatchery. The daily feeding ration ranged from 7% of body weight for the first month to 5% for the second month with a pelleted feed (30 – 35% crude protein), which was considered to the apparent satiation level, i.e., as much as the fish can eat in 15 minutes. Feeding was done by hand twice daily to support the optimal growth and development of the tilapia fry.

2.5 Growth performance study

Weight of 25 randomly caught fingerlings from each hapa was measured to the nearest 0.01 g using an electronic balance during sampling at fortnight interval. The fish were reared in the cages for 90 days. Growth performance indicators (average final body weight gain, AFBWG; final biomass production, FBP; biomass gain, BG; mean weekly body weight gain, MWBWG; specific growth rate, SGR) were calculated following Yengkokpam *et al.* (2020), using the following equations. AFBWG = final average body weight (FABW) – initial average body weight (IABW); AFBWG × survival rate; final biomass (FB) - initial biomass (IB); AFBWG / w; [(In FABW - In IABW)/t × 100 where, *t* is the number of culture weeks and *In* is the natural log. For calculation of feed conversion ratio (FCR), the total dry weight of feed given (not corrected for feed loss) was used and is calculated as FCR = total dry weight of feed offered / BG. Daily mortality was noted and survival rate was calculated. Survival rate (%) = (Number of fish harvested / number of fish stocked) × 100. To reduce the stress during handling, fish were sedated by light sedation using Aqui-S anaesthetic provided in an aerated water bath at 0.2 ml $5L^{-1}$.

2.6 Economic viability study

The economic analysis was done as described by the Jolly and Clonts (1993). Fixed costs (FC) were related to hapa and cage construction and depreciation costs; whereas variable costs (VC) were related to feed, fry, labour, medicine and miscellaneous costs. Total cost (TC); gross revenue (GR); gross margin (GM); net profit (NP); benefit-cost ratio (BCR) and profitability (%) were calculated as TC = FC + VC; GR = total biomass × farmgate value; GM = GR – VC; NP = GR – TC; BCR = GR/TC and profitability = NP/TC x 100. The farmgate value of fingerlings produced in different treatments was considered as BDT kg^{-1} [1 US$ = BDT 80].

2.7 Community's economic benefit analysis

Before starting the experiment, socio-economic data of the fishers who participated in this study were collected. The data (e.g. education level, land resources and sources of income) were collected using a pre-structured questionnaire at the trial's commencement (Bhuiya *et al.* 2021). The active participation of household fishers, in this study, was meticulously recorded through fortnightly observations and monitoring by the research team throughout the study period. The trend in annual income of the resource-poor community fishers, was documented before the introduction of the present research and after the adoption of overwintering technique (for subsequent crops) for producing tilapia fingerlings in the hapa cum cage aquaculture system to observe any changes. Typically, these fishers used their annual income (generated mainly from natural fish catching) for daily sustenance and other subsistence activities.

2.8 Analysis of water quality parameters

Follow-up monitoring of water quality parameters (e.g. water temperature, water current, wave length and height, dissolved oxygen, pH and total ammonia) were carried out on a fortnight basis during the entire period of the experiment. Water temperature was measured in situ using a mercury-filled Celsius thermometer. Wave length and height were measured by Aanderaa Wave & Tide Sensor (Model 5218/5218R, Norway). Water current velocity was measured by Rotameter (2400 Lph, India), following the manufacturer's guidelines. Dissolved oxygen, pH and total ammonia were measured using HACH kits (model FF-2, USA) following manufacturer's protocol.

2.9 Data analysis

Statistical analysis was conducted using SPSS (version-20) following the method outlined by Steel and Torrie (1980). Analysis of variance (ANOVA) was utilised to assess differences in monosex tilapia fry overwintering performance (growth and economic viability) across the study areas. Before performing ANOVA, a normality test was conducted on the main dependent variable to determine whether the data followed a normal distribution. Subsequently, a post-hoc multiple range test was executed to evaluate the significance of differences among the means of the key dependent variable.

3 | RESULTS

3.1 Growth performances

The overwintering performance of tilapia fry in hapas cum cages was successful in haor areas, ensuring the availability and early supply of fingerlings for successful cage aquaculture. Significant differences were observed in all growth performance parameters, except the initial average body weight, under different stocking densities (Table 1). Increasing the stocking density from 200 to 250 m^{-3} and from 250 to 300 m^{-3} resulted in approximately 10% and 5% decreases respectively, in average final weight gain (which varied significantly; p < 0.05). Similar trends were noted in mean weekly body weight gain (MWBWG), SGR and survival rate (SR). MWBWG decreased significantly by around 10% in T_2 compared to T_1, and it lowered by about 7% in T_3 compared to T_2. A 3% reduction in SGR was observed in T_2 compared to T_1 and a 2% drop was noted in T_3 compared to T_2, with both differences being significant ($p < 0.05$). The highest survival rate was found in T_1, which was 2% higher than T_2 (not significant; $p > 0.05$) and 18% higher than T_3 (which varied significantly; $p < 0.05$). In contrast, both final biomass production (FBP) and biomass gain (BG) were approximately 10% and 5% higher in T_2 compared to T_1 and T_3 respectively (both varied significantly; $p < 0.05$). No significant variation was observed in FCR between T_1 and T_2, but both differed significantly from T_3, where an approximately 12% higher FCR was observed than in T_1 and T_2.

The subsequent outcomes from the best treatment (T_2) showed remarkable improvements in the 2nd and 3rd crops when compared to the initial results in the 1st crop, T_2 (Table 1). Despite the IABW of the tilapia fingerlings remaining consistent at 1.25 ± 0.25 g across all three crops, substantial progress was evident in various parameters. AFBWG saw a percentage increase of 22.29% from the 1st crop to the 2nd crop and an additional 8.39% in the 3rd crop. A similar upward trend was observed in FBP, with a 37.5% increase in the 2nd crop and a subsequent 7.97% rise in the 3rd crop. Biomass gain per cage exhibited a notable percentage increase of 28.38% from the 1st crop to the 2nd crop and a further 8.62% rise in the 3rd crop. MWBWG experienced a significant percentage increase of 136.36% from the 1st crop to the 2nd crop, followed by 11.54% boost in the 3rd crop. SGR displayed an escalating trend, with a 5.02% increase from the 1st crop to the 2nd crop and a subsequent 1.9% rise in the 3rd crop. Furthermore, the FCR demonstrated consistent enhancement, with a 2.5% reduction in the 2nd crop and an additional 1.03% decrease in the 3rd crop. Notably, SR remained consistently high and stable, reflecting the efficacy and sustainability of the applied aquaculture technique. These trends underscore the substantial improvements in tilapia growth, biomass production, and overall aquaculture efficiency over successive crops.

TABLE 1 The growth performance data of stocking and harvest parameters during overwintering of monosex tilapia fingerling production in hapas cum cage aquaculture in haor waters.

Parameters	**Treatments**			**Subsequent output of best treatment**		
	T_1 (*n* = 200)	**T_2 (*n* = 250)**	**T_3 (*n* = 300)**	**1^{st} crop (C_1)**	**2^{nd} crop (C_2)**	**3^{rd} crop (C_3)**
IABW (g)	1.25±0.25	1.25 ±0.25	1.25±0.25	1.25±0.25	1.25±0.25	1.25±0.25
AFBWG (g)	$58.86±7.23^c$	$52.75±4.21^b$	$50.20±7.72^a$	$52.75±4.21^b$	$64.57±7.1^a$	$69.89±6.78^a$
FBP (kg m^{-3})	$10.21±0.23^b$	$11.2±0.42^{ab}$	$10.72±0.19^a$	$11.2±0.42^b$	$14.35±3.01^a$	$15.52±3.19^a$
BG (kg $cage^{-1}$)	$202.48±14.55^b$	$222±18.61^{ab}$	$212.46±13.76^a$	$222±18.61^b$	$284.50±24.76^a$	$307.70±31.66^a$
MWBWG (g $week^{-1}$)	$0.49±0.01^c$	$0.44±0.00^b$	$0.41±0.01^a$	$0.44±0.00^b$	$1.04±0.11^a$	$1.16±0.21^a$
SGR (% day^{-1})	$3.08±0.01^a$	$2.99±0.01^b$	$2.94±0.02^c$	$2.99±0.01^b$	$3.15±0.02^a$	$3.21±0.12^a$
FCR	$1.96±0.07^b$	$2.00±0.11^b$	$2.23±0.10^a$	$2.00±0.11^a$	$1.95±0.10^a$	$1.93±0.09^a$
Survival (%)	$87.1±2.63^a$	$85.37±3.98^a$	$72.08±1.78^b$	$85.37±3.98^a$	$89.18±4.01^a$	$89.06±3.97^a$

Mean values (±SD) in the same row having the different superscript letter are significantly different ($p < 0.05$).

3.2 Economic viability

The economic feasibility depends on comparatively lower amount of total cost (FC + VC) required than the higher amount gross margin. In the assessment of economic aspects across treatments (T_1, T_2 and T_3), notable differences emerged, expressed as percentages (Table 2). The FC remained constant at 44.60 across all treatments. However, the VC varied significantly, with T_3 incurring the highest cost, constituting around 11.2% increase compared to T_2 and a substantial 29% increase in comparison to T_1. Consequently, total costs followed a parallel pattern, with T_3 being the most expensive, marking about 10% and 26% increase over T_2 and T_1 respectively. In terms of revenue generation, T_2 and T_3 outperformed T_1, showcasing notable differences. Gross margins mirrored these trends, with T_2 showing the highest margin, indicating around 45% increase over T_1 and about 32% increase over T_3. Net profits underscored the profitability disparities among the treatments. T_2 led the way with a remarkable 68% increase over T_1 and about 47% increase over T_3. The benefit-cost ratio highlighted the economic feasibility of T_2, showing a 7.63% and 7.76% improvement, respectively, over T_1 and T_3. Lastly, profitability percentages also showcased T_2 as the most profitable, with around 47% increase over T_1 and about 64% increase over T_3. These findings underscore the economic advantages of T_2, highlighting its potential for enhanced profitability and cost-effectiveness in comparison to the other treatments.

In the subsequent crops of the best treatment (C_1, C_2 and C_3), various economic parameters exhibited significant changes (Table 2). The FC remained stable at 44.60 across all crops. However, the VC displayed noticeable fluctuations, with C_2 witnessing the highest increase, incurring 15% higher costs compared to C_1, whereas C_3 experienced a 3.5% decrease compared to C_2. Consequently, total costs followed a similar trend, with C_2 becoming the most expensive, showing an increase of 3% compared to C_3 and around 13% increase compared to C_1. Regarding revenue generation, C_2 and C_3 demonstrated impressive growth, with both achieving around 14% increase compared to C_1, indicating their enhanced economic viability. Gross margins showed C_3 exhibiting the most significant rise. Net profits underscored the profitability of the crops, with C_3 leading with a 14% and 4.5% increase compared to C_1 and C_2 respectively. The benefit-cost ratio highlighted the economic feasibility of C_3, demonstrating about 3% improvement over C_2 and a 1.5% improvement over C_1. Lastly, profitability percentages illustrated C_3 as the most profitable, indicating around 12% higher than C_1 and around 13% higher than C_2. These findings emphasize the economic advantages of C_3, showcasing its potential for enhanced profitability and cost-effectiveness compared to the other crops.

The VC accounted for 92% of the total expenses in the first crop, while the FC constituted only 8%. Notably, feed cost and seed cost accounted for significant portions of the variable costs, comprising 72% and 27% of VC respectively. These percentages remained relatively consistent across the three crops, indicating stability in variable costs, while fixed costs remained constant. Further analysis of the variable costs revealed that feed cost constituted nearly three-quarters of the total variable expenses, with seed cost making up around one-fourth. Interestingly, seed cost was significantly higher in the first crop compared to subsequent crops.

TABLE 2 The comparative cost benefit analysis of tilapia fry nursing in hapas cum cage among the all treatments.

Cost issues	Items	Treatment			Subsequent crops of best treatment		
		T_1	T_2	T_3	C_1	C_2	C_3
Fixed cost (FC)	Hapa cost	37.50	37.50	37.50	37.50	37.50	37.50
	Depreciation cost (hapa+cage)	7.10	7.10	7.10	7.10	7.10	7.10
	Sub total	44.60	44.60	44.60	44.60	44.60	44.60
Variable cost (VC)	Feed	331.96 ± 15.41^{b}	373.14 ± 1753^{a}	401.16 ± 2073^{a}	373.14 ± 22.76^{b}	463.78 ± 18.86^{a}	460.07 ± 24.76^{a}
	Seed	123.88^{c}	154.84^{b}	185.81^{a}	154.84^{b}	142.46^{b}	123.88^{a}
	Labour	4.38	4.38	4.38	4.38	4.38	6.25
	Medicine	1.25	1.88	2.50	1.88	3.18	2.30
	Miscellaneous	1.50	1.50	1.50	1.50	1.50	2.10
	Sub total	462.96 ± 15.41^{c}	535.74 ± 17.54^{b}	595.35 ± 20.73^{a}	535.74 ± 17.54^{c}	615.29 ± 26.71^{a}	594.59 ± 19.88^{b}
Total cost (FC+VC)		507.56 ± 15.41^{c}	580.34 ± 17.53^{b}	639.95 ± 20.73^{a}	580.34 ± 17.53^{b}	667.89 ± 27.65^{a}	647.19 ± 34.76^{ab}
Gross revenue		604.28 ± 18.27^{b}	740.25 ± 34.32^{a}	749.64 ± 18.88^{a}	740.25 ± 34.32^{b}	828.53 ± 32.65^{a}	827.48 ± 38.44^{a}
Gross margin		141.31 ± 12.23^{b}	204.51 ± 13.01^{b}	154.29 ± 10.91^{a}	204.51 ± 13.01^{a}	168.63 ± 8.56^{a}	232.88 ± 14.65^{a}
Net profit		92.11 ± 14.24^{b}	155.31 ± 11.39^{b}	105.09 ± 14.92^{a}	155.31 ± 11.39^{a}	213.23 ± 14.44^{a}	180.28 ± 16.01^{a}
benefit-cost ratio		1.18 ± 0.01^{b}	1.27 ± 0.06^{b}	1.16 ± 0.05^{a}	1.27 ± 0.06^{a}	1.25 ± 0.11^{a}	1.29 ± 0.12^{a}
Profitability		18.15 ± 3.87^{a}	26.83 ± 2.1^{b}	16.44 ± 1.3^{a}	26.83 ± 2.1^{c}	26.35 ± 1.98^{b}	30.42 ± 4.32^{a}

Mean values (±Standard deviation) in the same row having the different superscript letter are significantly different ($p < 0.05$)

3.3 Community's economic benefit

The cumulative total annual income from overwintering hapas cum cage aquaculture exhibited increasing trends in subsequent crops (Figure 2). In the second and third cycles, 85% to 95% of community fishers managed to continue rearing tilapia fry in winter seasons using the technical knowledge acquired from the training. Prior to the introduction of hapas cum cage aquaculture, the annual income of resource-poor community fishers was 47.73% lower than the income of third crop. Previously, fishers utilised their yearly earnings from natural fish catching for daily sustenance and other essential activities. However, after adopting the overwintering of tilapia fry in the hapas cum cage aquaculture system, their gross and net income increased, enabling them to invest in medical assistance, essential electronic gadgets, and domestic devices.

3.4 Analysis of water quality parameters

The physico-chemical factors, such as water current, temperature, wave length of haor waters, dissolved oxygen, pH and total ammonia were measured and recorded fortnightly (Table 3). Only temperature showed a significant difference ($p < 0.01$), which might have had some effects on the growth performance of the tilapia fry. The remaining factors in the haor areas favoured the growth performance of tilapia fingerlings consistently.

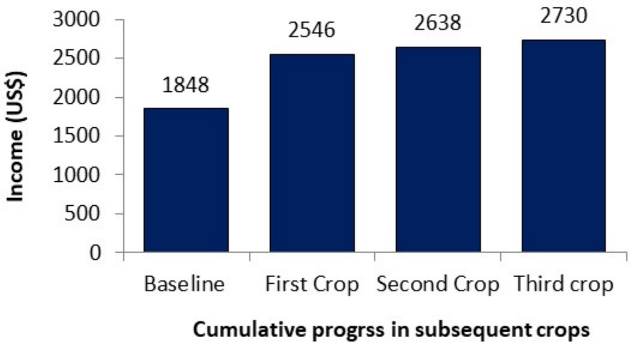

FIGURE 2 The cumulative total annual income from over-wintering hapas cum cage aquaculture in haor areas of Bangladesh.

4 | DISCUSSION

The findings indicate that varying stocking densities significantly influenced the growth performance and profitability parameters of tilapia fingerling production in haor areas. Treatment 2, with a stocking density of 250 fish m^{-3}, emerged as the most profitable option, outperforming other treatments in terms of final biomass production and biomass gain which were the key indicators of achieving the objectives of the present study. The study revealed consistent trends across multiple crops, demonstrating the economic viability of this stocking density for haor fishers.

In terms of growth performance, the study showcased substantial differences among stocking densities. The results comply with the observation of Huang and Chiu (1997); Ridha (2006); Gibtan *et al.* (2008); Ferdous *et al.* (2014); Kunda *et al.* (2021) who found significant divergence in growth parameters, particularly AFBWG, SGR and SR, with different stocking patterns. In the present study, increasing stocking density from 200 to 250 fish m^{-3} resulted in a 10% decrease in AFBWG and a subsequent 10% reduction in MWBWG, both of which were statistically significant. Additionally, SGR and SR showed similar trends, highlighting the impact of stocking density on these parameters. Yousif (2002) and El-Sayed (2002) found the negative relation of stocking density with the growth performance where the increase in stocking density had adverse effects on the FABWG, SGR and feed utilization specially protein efficiency ratio of stocked tilapia. Voluntary appetite suppression, energy loss due to antagonistic behaviour, competition of food and space (Kheir and Saad 2003) and involving higher stress (Diana *et al.* 2004) were reported as the possible reasons of the effects. Furthermore, researchers (e.g. Chowdhury *et al.* 2002; Zahedi *et al.* 2019; Liu *et al.* 2019) have found that lower stocking densities result in less stress in cultured fish contributing higher final weight gain.

TABLE 3 Water quality parameter data observed throughout the study period.

Parameters	First crop (*n* = 6)		Second crop (*n* = 6)		Third crop (*n* = 6)	
	Range	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD
Wave length (45–56 cm)	35 – 52	43.50±5.36	39 – 57	48.00 ± 8.36	32 – 55	43.50 ±5.11
Wave height (10–15 cm)	10–18	14.00 ± 3.55	14 – 22	18.00 ± 4.04	12 – 20	16.00 ± 3.15
Water current (cm sec^{-1})	12 – 25	18.50 ± 5.23	11 – 22	16.50 ± 4.22	15 – 24	14.50 ± 4.28
Water temperature (°C)	16.5 – 22.8	18.61 ± 4.44^{b}	17 - 26.6	22.3 ± 4.11^{a}	18.5 – 27.8)	23.2 ± 6.44^{a}
Dissolve oxygen (mg L^{-1})	4.8 – 6.5	5.52 ± 1.23	4.9 – 6.3	5.50 ± 2.2	5 – 6.7	5.53 ± 1.6
pH	7.2 – 8.8	8.00± 2.37	7.0 – 8.4	7.70 ± 1.89	7.2 – 8.4	7.80 ± 2.1
Total ammonia (mg L^{-1})	0.00	0.00	0.00	0.00	0.00	0.00

Mean values (± SD) in the same row having the different superscript letter are significantly different ($p < 0.05$). The data showed for the first crop were all same for the treatments (T_1, T_2 and T_3).

Importantly, in the current study, FBP (m^{-3}) and BG ($cage^{-1}$) demonstrated positive relations with stocking density, indicating that higher stocking densities led to increased biomass production and biomass gain. FBP and BG were notably higher in T_2 compared to both T_1 and T_3 with statistically significant differences observed. The positive relationship between stocking density and yield has been described in culture-based fisheries in cages and in reservoirs (Phan and De Silva 2000; Sugunan and Katiha 2004; Nguyen *et al.* 2005) where culture of all these species showed that the highest stocking density led to the highest biomass.

In terms of the FCR, an increasing trend was observed among treatments, with a higher FCR recorded in T_3. The FCR values in our study were slightly higher than those reported by Hossain *et al.* (2005) for monosex tilapia overwintering in pond conditions. This difference might be attributed to the better culture practices and suitable environmental conditions in the haor waters compared to the pond environment. Similar findings were reported by Gibtan *et al.* (2008); Osofero *et al.* (2009) and Assase *et al.* (2016) who suggested that the efficient utilization of diets associated with appropriate environmental factors resulted in higher FCR.

In the present study, T_1 demonstrated the highest SR, surpassing T_3 significantly and marginally outperforming T_2, suggesting that lower SR was attributed to the highest stocking density. Simillar findings were also reported by Chakraborty and Banerjee (2010) and Osofero *et al.* (2009) who argued that the increased competition for food and space, cannibalism and stress associated with high stocking density might result in decreased SR. Similar assumption was also made by Ferdous *et al.* (2014) where the highest stocking density of monosex tilapia fry provided the lowest survival rates and growth rates. In the present study, the SR of 1.25 g tilapia fry among treatments (72.08 to 87.10%) was much more higher than the SR of 1 g tilapia fry (54%) found by Dan and Little (2000) who overwintered tilapia fry (*O. niloticus*) in deep-hapas-in-ponds. A 32% SR was found with a stocking size of 0.4 g in overwintered *Oreochromis aureus* observed by Kamel *et al.* (2008) in hapa-pond system. This might be due to the higher susceptibility of small-sized fry to the environment compared to the large-sized fry. This statement was complied with the argument made by Charo-karisa *et al.* (2005) who found that smaller fish (<5 g) were more susceptible to lower temperature than larger fish.

The study revealed substantial improvements in tilapia cultivation across multiple parameters in successive crops. Notably, there were consistent percentage increases in key metrics, highlighting the efficacy of the applied strategies. The tilapia fingerlings exhibited significant gains in body weight, with a substantial 30.68% increase in AFBWG from the 1st to the 3rd crop. The FBP also saw a remarkable uptick, indicating a 38.55% rise over the same period. Additionally, the BG per cage increased by 30.59%, indicating enhanced productivity. The MWBWG displayed a significant surge, showing a 147.73% increase from the 1st to the 2nd crop, indicating robust growth rates. Furthermore, the SGR demonstrated a positive trend, indicating improved fish health and development. The consistent reduction in the FCR reflected enhanced efficiency in feed utilisation. Importantly, the stability in high SRs underscored the sustainability of the employed strategies. These insights emphasize the potential for fine-tuning aquaculture practices, ensuring both productivity and sustainability in tilapia cultivation over successive crops.

From an economic perspective, the findings of the present study revealed that T_2 stood out as the most profitable choice. It exhibited a 22.30% increase in revenue compared to T_1, showcasing its economic viability. Although T_3, with an even higher stocking density, exhibited a substantial boost in revenue compared to T_1 and T_2, it required higher investments because of higher stocking densities compared to other treatments. The common notion suggests that higher investments lead to greater profits, especially in ventures with high costs. However, in the context of small-scale farming prevalent in community-based cage aquaculture systems, the focus should not only be profit-oriented but also consider the investment capability (Kunda *et al.* 2014). NP reinforced these trends, with T_2 leading the way, showing a remarkable 68.21% increase over T_1 and a 47.48% increase over T_3. The BCR and profitability percentages also favoured T_2, underscoring its better profitability and cost-effectiveness. This aligns with the findings of Osofero *et al.* (2009).

The growth performance data in this study showed higher results in the second and third crops compared to the first crop through using the best treatment (C_2, stocking density of 250 fish m^{-3}). This improvement suggests that the training and skills provided to the fishers engaged in overwintered fingerling production had a positive impact. Previous research by Little and Hulata (2000) indicated that hapas nursing in pond systems was challenging, especially for entrepreneurs in the aquatic sector. However, in our study, the success can be attributed to the community-based fishers' group, which proved capable of managing all the necessary inputs and services required for successful cage management. Nasr-Allah *et al.* (2014) reported higher profitability in tilapia fry production by commercial hatcheries in Egypt using hapas-based systems (37.6%) compared to heated greenhouse-based systems (33.2%). The present study also proved that the profitability at hapa cum cage system (30.42% being highest) was higher compared to the hapa set in the pond system (23.18% being highest) (Mensah *et al.* 2013).

The overwintered tilapia fingerlings play a crucial role in the early stocking of cage aquaculture systems. Locating the production site locally is advantageous for efficient trading with local pond and cage owners, ensuring optimal results. The success of tilapia fingerling production relies significantly on technological knowledge and skill development acquired through training. These factors contribute to the consistent availability of appropriately sized fingerlings, leading to significantly higher biomass production in both the second and third crops. Identifying key technical aspects, such as stocking density and hapas positioning, along with physical factors, proved essential for the successful overwintering of tilapia fry in hapas. These insights are vital for the horizontal expansion of haor aquaculture production. The overwintering of tilapia fry in the hapas cum cage aquaculture system presents a straightforward and adaptable method, which could be seamlessly integrated into existing cage aquaculture systems.

The study revealed that the mean values of various water quality parameters, except temperature, did not differ across the three crops. This lack of significant differences can be attributed to the unbiased application of physico-chemical parameters as predictor variables. However, temperature values exhibited significant variation among the crops at a 10% level of significance, with the highest values associated with bright sunshine. Azaza *et al.* (2008) noted that a temperature of 22°C resulted in lower daily weight gain, while survival rates remained unaffected. Additionally, Hassan *et al.* (2013) found that lower temperatures, especially in shallow ponds, led to increased mortality. However, in the present study, the water temperature did not fall below 16.5°C which was consistent with the result found by Siddik *et al.* (2014). Charo-Karisa *et al.* (2005) found that tilapia reared under autumn condition died between 11.7°C and 7.5°C. In the present study, no such mortality was observed among treatments even in the subsequent crops. Dissolved oxygen values did not show significant differences among the three crops. The observed dissolved oxygen levels in the range of 4.8 – 6.7 mg L^{-1} align with the optimal dissolved oxygen levels for tilapia fingerlings production in cage systems (Kunda *et al.* 2021), falling within the optimal range (5 – 7 mg L^{-1}) suggested by Banerjee (1967). The pH values recorded in this study are consistent with the findings of El-Son *et al.* (2022) observed in Nile tilapia (*O. niloticus*) raised in hapa-in-pond system. The measured values were within the needed levels for *O. niloticus* growth (Boyd and Tucker 1998). Additionally, factors such as wave length, wave height, and water current remained insignificant across the crops, a result consistent with the research of Moller (1979). This study emphasises the positive influence of certain physico-chemical factors in haor waters, such as appropriate dissolved oxygen level and continuous water flow-through system in haor water, on fingerling production, surpassing the effects observed in seasonal ponds, even with improved water quality due to pond drying (Boyd and Bowman 1997).

In summary, the findings highlight the profitability and sustainability of stocking density at 250 fish m^{-3}, particularly in subsequent crops. Treatment T_2, with this stocking density, proved to be the most economically viable option, offering enhanced growth performance (from 52.75 to 69.89 g) and increased profitability (from 26.35 to 30.42%) for haor fishers. The successful adoption of overwintering practices has further contributed to the economic well-being of the community, emphasising the positive impact of these aquaculture techniques on the local economy and livelihoods. For the sustainability of cage aquaculture technique that ultimately enhance the income and livelihood of fishers community fishers; the overwintering of tilapia fry hapas cum cage aquaculture system is an excellent tool in this aspects. The study results showed a new way of using natural waters that contributed to the livelihood of stakeholders Therefore, this approach is essential for both the development of overwintered fingerling in hapas cum cage aquaculture system and for the betterment of the community households in the studied areas.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTION

SIB conceptualization, research design, data collection, formal analysis and interpretation, writing original draft; RCM writing original draft; review and editing, writing final draft; FK review, data interpretation; AKMNA investigation, supervision.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request to the corresponding author.

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