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Comparative juvenile performance assessment of genetically improved Nile tilapia (*Oreochromis niloticus* L.) under commercial conditions in Bangladesh

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Abstract

Two on-farm juvenile performance trials were conducted at a hatchery in Bangladesh to compare a genetically improved strain of farmed Nile tilapia (GIFT) and a local strain (LS) produced by commercial operators. A 21-day early nursing trial was conducted in five replicate hapas followed by a 27-day advanced nursing trial in six replicate hapas. The mean feed conversion ratios (FCR), mean specific growth rates (SGR), mean individual final weights, mean production yields and mean survival rates were calculated for both strains. During the early nursing trial, GIFT fry survival rate and overall yield were significantly ($p < 0.05$) greater than LS values, which in contrast demonstrated better FCR and SGR. Improved performance was demonstrated in terms of FCR, SGR and yield for GIFT during the advanced nursing trial and mean final individual weights were 78% greater for GIFT than LS fish (2.26 g and 1.27 g respectively). Economic analysis indicated GIFT fish produced a net return 84% greater than that of LS fish at the end of the early nursing period, and by the end of the advanced nursing period, this difference had grown further such that GIFT generated a gross return over double that of LS. The results from a survey of tilapia grow-out farmers suggested producers from poor, medium and better-off backgrounds agreed GIFT performed better than traditional strains and is beneficial for aquaculture growth in Bangladesh. However, the results also indicate there may be a greater propensity for better-off farmers to appreciate the potential benefits of improved strains over poorer farmers.

KEYWORDS
Bangladesh, farmer perceptions, growth, Nile tilapia, survival

1 | INTRODUCTION

Aquaculture production in Bangladesh has grown rapidly over the past three decades (4–10% annually) to meet rising demand. This demand has been attributed to stagnating capture fishery production, increasing household income and population growth (Belton & Azad, 2012; DoF, 2018; Toufique & Belton, 2014). Expansion of the sector has been facilitated by the development of aquaculture value chains through investments by thousands of actors and a diversification of the main commodity species (Hernandez et al., 2018). As a new entrant famed species, tilapia has become a significant foodfish commodity in Bangladesh since the turn of the millennium, particularly as production and consumption values have become better known.

Government and NGO led research investment programmes, focused on improving the aquaculture sector in Bangladesh, included the selective breeding of Nile tilapia (*Oreochromis niloticus*). This research agenda resulted in numerous introductions of improved strains across Bangladesh through multiple agencies (Hussain et al., 2013). One such selective breeding project which emerged in the late 1980s was the WorldFish Genetically Improved Farmed Tilapia (GIFT) programme (Eknath et al., 1993). GIFT was introduced to Bangladesh in 1994 with the expectation that it would alleviate issues such as poor hatchery management, genetic deterioration of broodstock and poor-quality seed (Eknath et al., 1993; Hussain et al., 2017; Towers, 2013; WorldFish, 2015). Owing partly to the introduction of improved strains (Gjedrem, 2012), Bangladesh now produces more than 380,000 tonnes of tilapia annually (DoF, 2018; Tran et al., 2021), making it one of the most important species by volume (Belton et al., 2011; Uddin et al., 2021). Further growth in production is expected to be stimulated by improved seed quality (Hussain et al., 2013) and intensification of practices such as commercial feed use, fertilization and stocking of advanced fingerlings.

During the selective breeding stage and the subsequent dissemination of GIFT, studies suggested improved strains had great economic potential for both producers and consumers (Dey, 2000), and it was claimed that investment in GIFT could benefit national economies (Ponzoni et al., 2007). Several ex-ante evaluations within the literature forecasted economic success for GIFT farmers. For example, Bimbao et al. (2000) found scope for significant improvement of tilapia production in the Philippines through the use of improved strains and improved farming practices, and they also suggested the average tilapia hatchery could double production and financial returns. Similarly, Dey et al. (2000) suggested GIFT could improve production in five Asian countries where improved strains were compared with local strains in on-farm trials. Their results indicated GIFT had superior growth and survival rates and claimed the superior performance would eventually benefit both producers and consumers as high yielding, and low-cost production would result in a decreased market price. Dey (2000) argued for the early adoption of GIFT indicating profitability would increase, market prices would be reduced, and there would be an increase in national fish consumption.

Early impact assessments of GIFT produced promising results and encouraged the dissemination and adoption of improved tilapia across Asia. Since then, many studies have assessed GIFT across Asia and South America and have drawn comparisons with other improved and non-improved strains. For example, several performance studies assess GIFT productivity and demonstrate how the higher production yields associated with improved strains produce greater economic returns (Omasaki et al., 2017; Ponzoni et al., 2011). Tran et al. (2021) recently compared GIFT and non-GIFT strains in Bangladesh and showed GIFT had superior growth rates and was more profitable than non-GIFT. Trinh et al. (2021) compared GIFT with an improved *O. niloticus* strain in Ghana which revealed GIFT had a significantly better growth rate but similar survival rate to the other strain. Dickson et al. (2016) demonstrated improved farm profitability for farms using genetically superior strains and improved management practices in Egypt. Similarly, Haque et al. (2016) compared the on-farm performance and profitability of GIFT with a strain of red tilapia in Bangladesh and reported a significantly higher growth and survival rate and higher economic return for GIFT. However, this study does not specify the generation or purity of the GIFT strain involved in the study. A lack of farm traceability along with the prolific inbreeding and introgression between farmed strains has caused significant uncertainties of tilapia genetics across the country. Consequently, many Bangladeshi fish farmers do not know which GIFT generation they are farming.

Inbreeding has caused major constraints within the industry as stunted growth and low value produce are common in poorly managed mixed-sex systems (Dan & Little, 2000a; Hussain et al., 2013; Little, 2004). In response to this, commercial operators began farming monosex populations to control breeding and recruitment in ponds which yielded significant performance improvements (Lind et al., 2015; Little et al., 2003; Tetteh-Doku Mensah et al., 2013). Male monosex farming systems have helped to prevent growth stunting by reducing competition for food and energy expended during courtship (Dan & Little, 2000a). Nevertheless, demand for mixed-sex seed remains strong (Little, 2004), possibly linked to a continuing demand for smaller sized fish. While 300–500 g tilapia attract a better market price, there are a vast number of people living in poverty for whom only smaller fish are affordable (Belton et al., 2014; Brummett, 2000). Additionally, mixed-sex farming circumvents the need to continuously repurchase seed and is generally less costly to establish and operate (Haque et al., 2010). This may be more attractive and viable for low-income Bangladeshi farmers, for whom there is a wide range of financial, social and nutritional benefits (Haque et al., 2014; Saiful Islam et al., 2015). This perspective has never been taken into consideration when studies have compared improved GIFT strains since the focus has always been on productivity. Some farmers may perceive faster growing, more expensive strains as less attractive if they are unable to afford the high inputs required for improved productivity. To address this, farmer perceptions and behaviours should be better understood and taken into consideration during the development of policies and interventions.

Although many mixed-sex tilapia farmers allow fish to free breed in ponds, there is still high demand for tilapia fry every year. Meeting this demand has led to the practice of nursing fry for prolonged periods to overcome intervals when spawning is constrained by climatic conditions (Little et al., 2003). Typically, farmers' stock fry into grow-out ponds at the beginning of the monsoon season before tilapia spawning has fully commenced. To ensure availability of seed at the beginning of the monsoon season, hatcheries often nurse fry in hapas over winter. Commercial hatcheries usually nurse tilapia fry for one month and sell for on-growing when they are still less than

1 g. However, the advanced nursing or 'overwintering' of fry means the fish are larger when purchased by grow-out farmers, which is preferred as survival rates increase with increasing size (Little et al., 2003; Mengistu et al., 2020).

WorldFish established tilapia breeding nucleuses (TBN) across Bangladesh to maintain genetic diversity of GIFT fish and to act as a reliable source of tilapia seed for commercial hatcheries. TBNs supply improved fry and broodstock to hatcheries which then supply thousands of commercial farms with improved fry for on-growing (Hussain et al., 2013). The Mymensingh TBN was established when germplasm of 14th generation GIFT was transferred from a WorldFish research station in Jitra, Malaysia. Improved seed from this germplasm has been produced and disseminated to hatcheries and farms across the country, ensuring tilapia producers have access to good quality seed and are encouraged to intensify tilapia production. Early on-station trials proved previous GIFT generations grew better (Dey et al., 2000; Ridha, 2006) and obtained a higher market price (Ahmed & Ahmed, 2009) compared with local strains, and WorldFish have consistently shown the genetic gains are cumulative (Khaw, 2016). However, further research is required to ensure the improvements made by WorldFish TBNs and other genetic improvement programmes are positively impacting the poorest.

This research project was designed to measure the impacts of GIFT by investigating production indices and economic performance of GIFT fry during the early nursing and advanced nursing stages of monosex seed production. Two strains of tilapia seed were assessed through on-farm trials which compared performance variables of GIFT with a traditional hatchery strain (LS). In addition, a survey of tilapia farmers from different socio-economic backgrounds documented farmers' experiences with, and perceptions of, GIFT tilapia.

2 | MATERIALS AND METHODS

On-farm, client-oriented research (OFCOR) is a participatory approach, which engages resource-poor farmers as collaborators during research activities (Biggs, 1989). This study employed a collegial OFCOR approach between farmers and scientists to strengthen organization and implementation of the research design. Collaboration between TBN farmers and researchers during the design stage ensured the research was client-oriented.

2.1 | Study site and experimental fish

Commercial hatcheries across Mymensingh were visited in May 2015, and hatchery owners were interviewed. A semi-structured questionnaire was used to identify the origin of hatchery broodstock, broodstock management practices and customer base. Through these discussions, researchers were able to identify a locally farmed strain (LS) to be used as the control strain for this study.

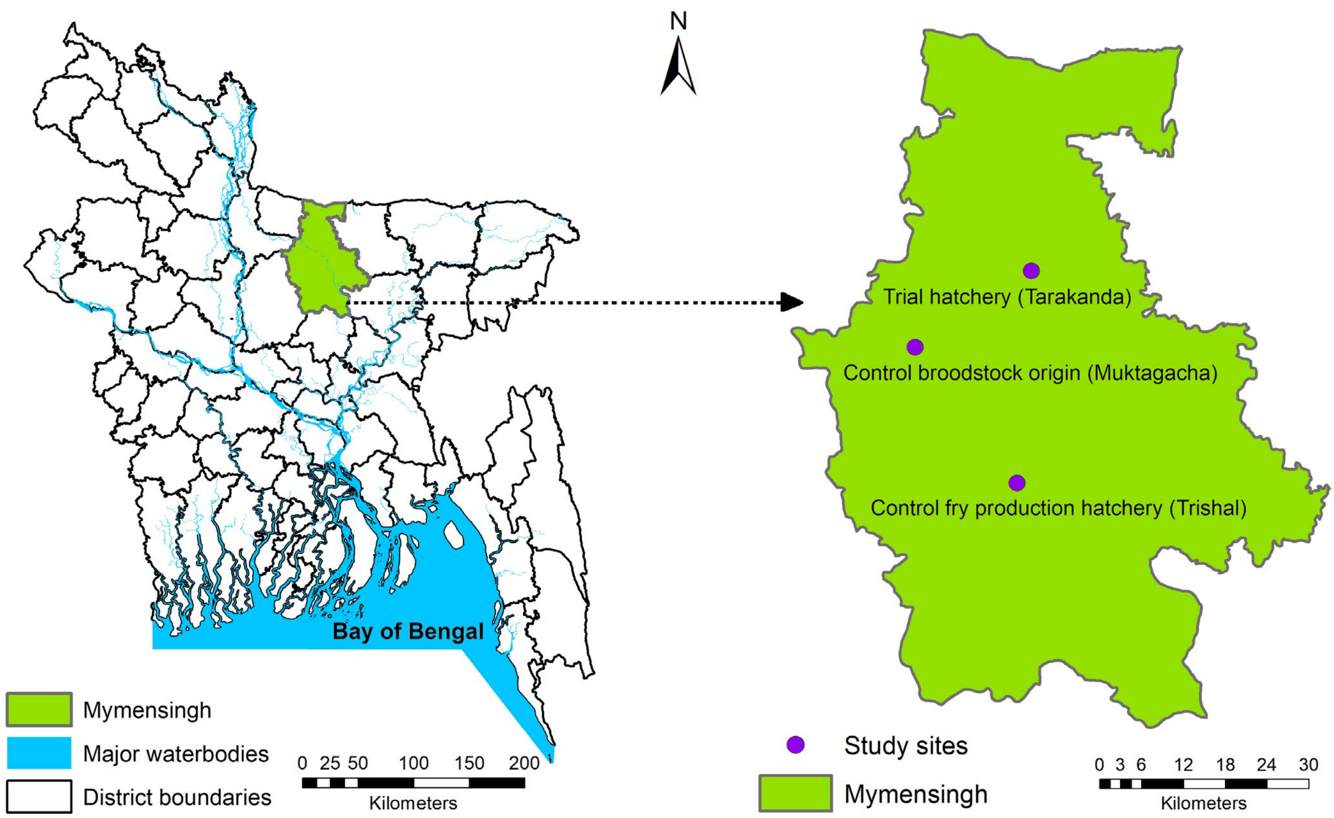

FIGURE 1 Location of study sites in Mymensingh, Bangladesh

The WorldFish TBN in Mymensingh (Figure 1) was chosen as the site for the experimental trials as Mymensingh is one of the largest tilapia producing districts in Bangladesh. The trials and farmer survey were conducted between May and July 2015.

GIFT fry produced by the Mymensingh TBN and a local strain (LS) produced by a hatchery in the Trishal sub-district of Mymensingh (Figure 1) were employed in the trial. LS (n = 50,000) fry were transferred to the experimental site one-day posthatch, and they were weighed and counted before being transported in oxygenated polyethylene bags (120 g fry 10 L^{-1}) by car. Upon arrival at the site, fry were transferred into a concrete cistern (2.3 m × 1.8 m × 0.3 m; water depth 0.22 m and water exchange rate was 2 L min^{-1}). One-day posthatch, GIFT fry were weighed and 50,000 were transferred into an adjacent cistern. Underground tube well water was pumped into an over-head tank, filtered and aerated to supply both cisterns. Both populations of fry received a floating, powdered commercial fish feed (MegaFeed; CP35%) which had been treated with 17α-methyltestosterone (MT) to induce all-male monosex populations (30% biomass day^{-1}). The feed was prepared by mixing 1 kg feed, 70 ml MT and 200 ml alcohol as per standard methods (Mair & Little, 1991).

2.2 | Broodstock management

LS broodstock originated from a farmer's pond in the Muktagacha sub-district of Mymensingh (Figure 1). Broodfish families had not been replenished since the beginning of the tilapia farming operation, several years earlier, signifying TBN GIFT fish had not been integrated into the stock. Over the years, LS broodfish were kept in ponds and moved to breeding hapas without proper management of families meaning some degree of inbreeding may have occurred. Conversely, broodstock origin, production and management practices at the GIFT hatchery (Mymensingh TBN) were well organized and well documented. TBN broodstock originated from 14th generation GIFT from Jitra, Malaysia. Sixty 'foundation families' were obtained and divided into eight cohorts, with each cohort kept in a separate pond. Genetic variability was maintained by shifting the males in each cohort to mate with the females of a different cohort each year (Hussain et al., 2017).

TBN and LS broodstock ponds were prepared by draining, drying and applying lime and fertilizer (1 kg calcium carbonate 40.5 m^{-2}, and urea and Triple Superphosphate at the rate of 200 g m^{-2} and 100 g m^{-2} respectively) before stocking. As per standard TBN practice, broodstock ponds (364.3 m^2) were stocked at the rate of 1.2 fish m^{-2} (1:3 male to female ratio). LS hatchery standard practice involved stocking broodstock ponds (2000 m^2) at the rate of 4 fish m^{-2} (sex ratio unknown). The GIFT and LS fry were produced from broodstock of similar age (12–18 months) and size (250–350 g), which had been fed with the same commercial floating feed (Mega Feed, CP 35%).

2.3 | Experimental pond preparation

The trial pond (347 m^2) was drained and dried, and then, quicklime was added at a rate of 1 kg 40.48 m^{-2}. The pond was subsequently filled with water pumped from adjacent, unstocked ponds and hapas were set for the beginning of the early nursing trial. During the preparation and throughout the trial, key water quality parameters (temperature, dissolved oxygen, pH, nitrite, nitrate, hardness, carbonate hardness and chlorine) were monitored and remained within the acceptable range for tilapia culture (El-sayed, 2020).

2.4 | Experimental design

2.4.1 | Early nursing trial

Fry were transferred to rectangular fine mesh (1 mm) net hapas (6.5 m^2) seven days posthatch. Both strains of fry had five replicate hapas randomly distributed across the pond, and each hapa was stocked with 4633 fry (712 m^{-2}). Fry were fed a hormone (MT)-treated commercial powder feed at the rate of 30% total biomass d^{-1} during week one and week two, and 15% biomass d^{-1} during the final week. Weight sampling occurred every seven days, and feed amount was adjusted accordingly.

All fry were collected at the end of the early nursing trial. Individual weights were recorded, and total harvest yields were calculated as number of fry m^{-2}. The following equations were used to determine the growth and survival rates for both strains.

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

$$\text{Feed conversion ratio} = \frac{\text{Total weight (g) of feed}}{\text{Weight gain (g)}}$$

$$\text{Specific growth rate (\%/day)} = \frac{\text{Log Final Weight} - \text{Log Initial Weight}}{\text{number of days}} \times 100$$

$$\text{Survival rate (\%)} = \frac{\text{No. of fish at harvest}}{\text{No. of fish at stocking}} \times 100$$

2.4.2 | Advanced nursing trial

Following the early nursing trial, all experimental fish were collected and graded into two size classes using 8-mm mesh graders. To reduce size discrepancies, fish from the small size class were employed in the advanced nursing trial. Hapas were cleaned and reset in the same pond one day after concluding the early nursing trial, and 1950 fish (300 fish/m^{-2}) were restocked into each hapa (area 6.5 m^2). Fry were fed commercial powdered feed at the rate of 15% and 10% of their bodyweight for the first 14 days and last 13 days respectively. This was adjusted weekly throughout the trial after sample weighing. The feed composition was identical to the feed used in the first trial; however, there was no hormone added. Both strains had six replicate hapas randomly distributed throughout the pond. Growth performance, survival and production rates were measured using the methodology mentioned above.

2.5 | Economic analysis

Cost-benefit analysis was performed using a partial budget approach (Tigner, 2013) to determine the net return for both strains produced during the trials. This approach is often used by farm business owners to make decisions regarding incremental changes to farming operations, for example adding land or changing a specific farming practice. Partial budgeting focuses on the specific economic impacts of the proposed change by only considering resources that will be altered, and disregarding resources that remain unaltered. Using this approach allowed us to assess any potential gains at that could be made at hatchery level through the production of GIFT fry over local strains.

Resources accounted for during each trial were feed, hormone treatment and tilapia fry sales. Land, labour, equipment and other resources remain unchanged and, therefore, are unaccounted for in partial budgeting.

The net income (NI) generated by each strain for both trials was determined by finding the difference between total costs (TC) and total returns (TR):

$$NI = TR - TC$$

where TR corresponds to the gross income from tilapia fry sales, and TC corresponds to the total costs for feed and monosex hormone treatment.

2.6 | Farmer perception survey

The survey aimed to compare tilapia farmer perceptions of GIFT and to establish whether farmer well-being category influenced those perceptions. Grow-out farmers (n = 30) from five districts (Mymensingh, Sherpur, Netrokona, Moulovibazar and Sunamgong) that had previously purchased seed from the Mymensingh TBN were chosen at random from a list of 150 customers and were contacted in June 2015. Farmers were only included in the survey if they had completed a full cycle of both GIFT and a local strain. Local enumerators assisted with the design, pre-testing and implementation of the questionnaire. Data collection was carried out in the local language by trained enumerators and based on local units of measurement that were later converted to SI metrics. Raw data were entered into an Excel spreadsheet and verified against original responses on the field questionnaire before analysis.

A one-off, two-part questionnaire was used to determine the socio-economic status of farmers and characteristics of their farming operations, and their perceptions of GIFT tilapia. Participants were asked a series of questions regarding land ownership, educational status, farming operations and household characteristics to determine their socio-economic status and were grouped into three well-being categories depending on their responses (better-off, medium and poor). They were then asked Likert-scale styled questions (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree and 5 = strongly agree) relating to GIFT production. The relationship between farmer well-being category and farmer perceptions of GIFT was then investigated.

2.7 | Statistical analysis

Data collected during the growth performance trials were analysed using Microsoft® Office 365 Excel 2013 version 15.0. Student's t test was used to determine performance differences, and results showing a p-value <0.05 were considered significant. Results are presented as means ± standard deviation.

RStudio version 4.0.3 was used to analyse the farmer survey data. Farmers provided a Likert-style score for each question asked regarding their perception of GIFT seed. The scores were added together to give each farmer an overall score which was termed the overall opinion score (OOS). ANOVA was used to investigate the differences in the perceptions of GIFT (OOS) by farmers from different well-being categories using the lm() function (Chambers, 1992), controlling for tilapia production levels, farm size and farmer aquaculture experience.

3 | RESULTS

3.1 | Experimental nursing trials

Growth performance and survival rates for fry produced in both trials are shown in Table 1. Baseline values for both trials differed between strains where GIFT demonstrated a slightly higher individual initial weight. Initial weights for the advanced nursing trial were slightly smaller than the final weight at the end of the early nursing trial as the smaller size class for both strains were used. Means without standard deviation are presented in Table 1 for initial weights as the fish were bulk weighed to reduce excessive handling of fry.

During the early nursing trial, LS had a significantly ($p < 0.01$) higher mean SGR than GIFT (16.42 ± 0.3 and 15.37 ± 0.18 respectively). However, during the advanced nursing trial, GIFT had a significantly ($p < 0.01$) higher mean SGR (6.34 ± 0.27 and 4.86 ± 0.36 respectively). Throughout the early nursing trial, GIFT survival rate was significantly ($p < 0.01$) higher than LS (88.5% and 70.9% respectively), but mean survival rates during the advanced nursing trial were not significantly different. For both trials, GIFT had a significantly ($p < 0.01$) higher individual final weight (Figure 2).

Unlike adult fish, which is sold to markets in weight, hatcheries typically sell fry in numbers. Farm-gate price for 28-day posthatch GIFT and LS fry (early nursing trial fry) was BDT 1 fish^{-1} and BDT

TABLE 1 Results of growth and survival indices during both trials

	Twenty-one-day early nursing trial		Twenty-seven-day advanced nursing trial	
	GIFT	LS[1]	GIFT	LS
Mean initial weight (g)	0.018	0.012	0.4	0.33
Final weight (g) (mean ± *SD*)	0.454 ± 0.018[a]	0.378 ± 0.023[b]	2.264 ± 0.17[a]	1.265 ± 0.12[b]
SGR (%) (mean ± *SD*)	15.37 ± 0.18[a]	16.42 ± 0.3[b]	6.34 ± 0.27[a]	4.86 ± 0.36[b]
FCR (mean ± *SD*)	1.39 ± 0.126[a]	1.2 ± 0.04[b]	1.42 ± 0.073[a]	1.98 ± 0.194[b]
Survival rate (%) (mean ± *SD*)	88.53 ± 1.2[a]	70.88 ± 2.4[b]	69.32 ± 12.4[a]	69.96 ± 5.9[a]

Note: Survival rates are not cumulative; they only represent survival rates for the individual trial.
[ab]Notations a and b are to compare means. Different superscripts indicate a significant difference (horizontal comparison within trials).
[1]Number of replications fell to 4 after one hapa was destroyed by a storm in the first week of the trial.

0.7 fish^{-1} respectively. This rose to BDT 2 fish^{-1} and BDT 1 fish^{-1} for GIFT and LS fry respectively in the subsequent advanced nursing trial. These market prices were based on information collected during discussions with tilapia farmers and hatchery operators.

An economic analysis of both strains produced in this study is presented in Table 2. The production yield of GIFT during the early nursing trial was significantly ($p < 0.01$) higher than that of LS (631.05 ± 8.6 and 505.2 ± 17.3 fry m^{-2} respectively). Conversely, no significant difference was found between production yields during the advanced nursing trial. The net return was much greater for GIFT fry in both trials owing to GIFT's superior production yield during the early nursing trial and greater market price.

3.2 | Results of farmer perception survey

Table 3 shows the basic farm characteristics for those involved in the farmer perception survey. All participants were male, aged 22–60, had between 4 and 18 years of education, had 3–20 years fish farming experience and had listed aquaculture as a primary or secondary occupation. Farming practices varied in terms of fertilizer use and water exchange; however, all farmers fed tilapia a commercial pelleted feed (Table 3).

Survey results can be seen in Figure 3 where farmer overall opinion scores have been disaggregated by farmer well-being category. Although the differences were not statistically significant, poor farmers were found to have the lowest mean OOS.

Survey results show around 50% of all farmers believed GIFT had a higher market demand and a higher market price than traditional strains; however, less poor farmers agreed with this when compared to better-off and medium farmers. Farmers were asked whether they perceived GIFT to have superior growth compared with traditional strains and 60% of poor farmers agreed, whereas 100% and 90% of better-off and medium farmers, respectively, agreed with this. A higher percentage of poor farmers (80%) perceived GIFT seed to be more costly compared with better-off (45%) and medium (43%)

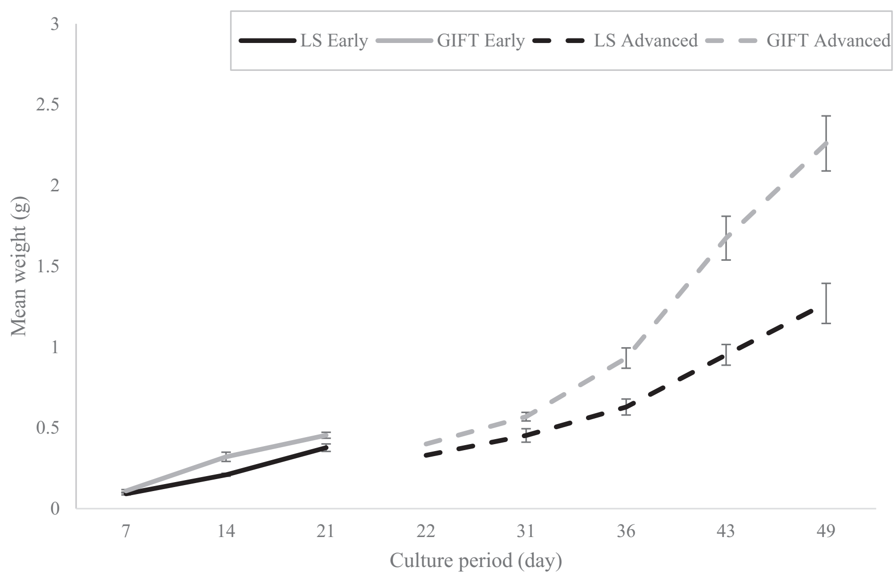

FIGURE 2 Growth performance of GIFT and LS strains of Nile tilapia for the total period of both trials (means ± *SD*)

TABLE 2 Mean production yields and economic analysis for both trials

	Production yield (fry/m^2) (mean ± *SD*)	Mean gross return (BDT/m^2)	Costs (BDT/m^2)	Mean net return (BDT/m^2)
Early nursing trial				
GIFT	631 ± 9[a]	631.05	65.48	565.57
LS	505 ± 17[b]	353.64	47.20	306.44
Advanced nursing trial				
GIFT	208 ± 37[a]	415.94	47.40	368.54
LS	210 ± 18[a]	209.9	32.56	177.34

[ab]Notations a and b are to compare means. Different superscripts indicate a significant difference (vertical comparison within trial).

TABLE 3 Farmer and farm characteristics disaggregated by well-being group

	Poor (*n* = 5)	Medium (*n* = 14)	Better-off (*n* = 11)
Age (mean years ± *SD*)	41.6 ± 11.9	42.6 ± 9.7	43.4 ± 10.6
No. household members (mean ± *SD*)	4.8 ± 0.4	7 ± 3.7	5.4 ± 1.6
Farmer education level (mean years ± *SD*)	10 ± 1.5	11 ± 3.6	12 ± 3.2
Aquaculture as primary occupation (%)	80	50	18
Aquaculture experience (mean years ± *SD*)	11 ± 5.3	8 ± 5	9.2 ± 6.2
Ponds owned (mean hectares ± *SD*)	3.8 ± 1.7	2.9 ± 2.8	13.2 ± 34.1
Tilapia as a % of total production	90	94.7	90.6
Farmers using fertilizer (%)	20	57	100
Farmers using commercial pellet feed (%)	100	100	100
Farmers practising improved water management (water exchange) (%)	60	69	63

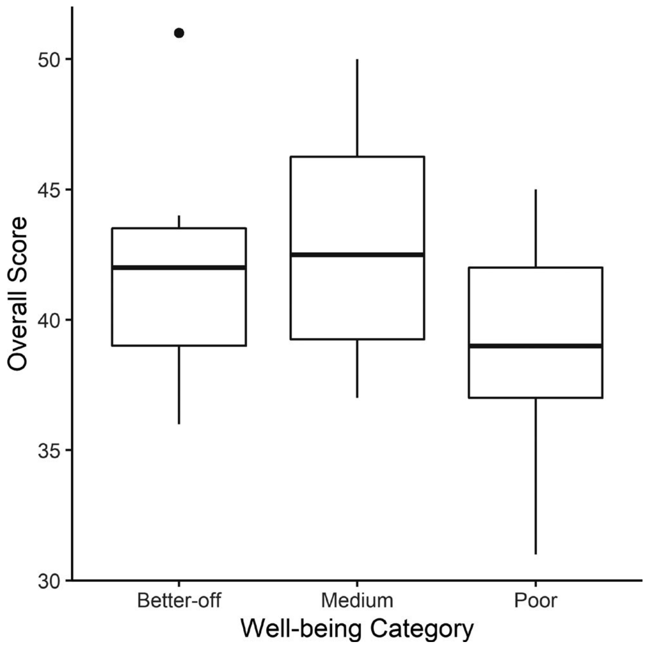

FIGURE 3 Overall opinion score for farmers disaggregated by well-being category

farmers. However, the differences between responses from farmers in poor, medium and better-off well-being categories were not found to be statistically significant.

4 | DISCUSSION

The objective of this study was to compare key performance indicators for GIFT and non-GIFT tilapia seed and to investigate fish farmer perceptions of GIFT in Bangladesh. On-farm trials confirmed GIFT had greater survival and growth rates in the early nursing stage and advanced nursing stage, resulting in a greater economic return at both stages when compared to a local strain. The farmer perception survey revealed the majority of farmers from poor, medium and better-off well-being categories agreed GIFT was more productive and likely to be beneficial for aquaculture growth in Bangladesh. Although no significant difference was found, results indicate better-off farmers had a greater propensity to agree that GIFT performs better than local strains, suggesting better-off farmers are more likely to appreciate the potential benefits compared with poor farmers.

GIFT fry had a statistically significant higher survival rate than LS fry during the early nursing trial, however, FCR and SGR were significantly ($p < 0.05$) superior for LS. Lower survival (LS) rates may account for this as more food would have been available for the remaining fry since feeding rates were adjusted depending on fish weights, without taking fish numbers into account, as per standard farming practices. The final production yield of GIFT was significantly greater than LS in the early nursing trial due to GIFT's greater survival rate (631.05 ± 8.6 and 505.2 ± 17.3 fry m^{-2} respectively).

These results suggest a hatchery producing GIFT fry would obtain a net return almost double of a LS hatchery due to GIFT's higher farm-gate price and higher production yields. The results from this study align with similar studies which show GIFT has superior growth to various other strains (Haque et al., 2016; Santos et al., 2014; Tran et al., 2021). For example, Trinh et al. (2021) recently compared the 11th generation of GIFT with an improved local Ghanaian strain (Akosombo), wherein GIFT was found to demonstrate significantly better growth rates.

In general, the GIFT strain had superior growth compared with LS during both trials. Although similar studies have produced comparable results when comparing GIFT to other strains (Dickson et al., 2016; Haque et al., 2016; Hussain et al., 2013; Tran et al., 2021), it must be noted that LS broodstock were fed 1% bodyweight per day compared with GIFT broodstock which were fed 2–3% bodyweight per day. This could have led to the yolk sac of LS fry being less nutritive, leading to decreased growth performance (El-Sayed et al., 2003). To ensure full control over such variables, future research should include management practices at every stage of production to ensure tilapia performance assessments consider all aspects of cultivation from fertilization through to harvest. Additionally, identification of optimal management practices for tilapia broodstock culture is needed to ensure production of high-quality larvae across the industry.

When looking to enhance the overall production of tilapia, it could be presumed that an improvement at hatchery level (quality broodstock and/or best management practices) will benefit value chain actors involved in the latter stages of production (Little et al., 2003). During this study, significantly higher survival rates for GIFT in the early nursing stage resulted in improved financial returns. Elevated growth rates of improved strains enable fingerlings to reach a marketable size faster, reducing production costs. The higher marketable value of GIFT compared with local strains is likely to boost both hatchery and nursery profit margins. At the final stage of production (the grow-out farm), greater availability of larger fingerlings for stocking has been seen to improve growth rates (Dan & Little, 2000b). This demonstrable growth premium over local strains would result in tilapia grow-out farmers benefitting financially from the sale of larger fish or more rapid production of smaller fish.

Results from the farmer perception survey show poorer farmers scored a lower OOS, suggesting they may be less likely to appreciate the benefits of farming a genetically superior strain of tilapia when compared to farmers from better-off and medium well-being groups. Poor farmers were less likely to agree that GIFT obtained a higher market price, had a higher demand, better productivity and was beneficial for aquaculture. However, they were more likely to agree that GIFT seed was more expensive than LS seed. The inability and reluctance of poor tilapia farmers to pay a higher price for improved seed or invest in improved farming practices have been discussed in the literature. Belton and Azad (2012) explain that 72.7% of better-off fish farmers in Bangladesh practice improved pond management, whereas only 29.9% of poor fish farmers are doing so. Similarly, a higher number of better-off and medium farmers involved in this study used fertilizer and improved water management compared with poor farmers. This may explain why a higher percentage of better-off farmers agree GIFT displayed better productivity and is more profitable since enhanced pond management would lead to improved growth rates. Karim et al. (2011) also demonstrate how farmer socio-economic background and farm location can influence the level of inputs used. They discuss differences in farmer behaviour and show poorer farmers apply lower-cost feeds/fertilizers compared with better-off farmers who tend to apply more expensive inputs. The productivity of a farm is dependent on many factors including strain of fish, level and quality of inputs, market demand etc. Poorer farmers may be less likely to appreciate the benefits of a genetically improved fish strain since less intensive farming practices would produce lower yields and economic returns. Additionally, poorer farmers may not view GIFT as beneficial for the aquaculture industry as better-off farmers are more likely to prioritize profit while poor farmers prioritize consumption needs and other activities (Ruben, 2007).

Overall, results from the farmer survey show most participants believed production was superior when using GIFT compared to traditional strains. This provides an insight into farmer perceptions however the study results could have been made more reliable had there been a larger number of survey participants spread more broadly across Bangladesh. This was beyond the scope of our study, but further assessments of farmer perceptions are required to understand the value of improved tilapia strains to poorer farmers. Tran et al. (2021) claim GIFT is more accessible to resource-poor farmers in Bangladesh compared with non-GIFT fish; however, their comparison study did not include strains which were considered unimproved or traditional. Researchers should include less developed strains when considering affordability, accessibility and productivity of various tilapia strains since many farmers are still producing mixed-sex fish. A study by Pemsl et al. (2008) found tilapia farmers preferred non-GIFT with regards to several characteristics including colour, taste and market demand. However, the performance characteristics analysed in the perception study were not believed to influence strain selection, and the authors suggest selection criteria may lie with other factors such as distance to hatchery. They found GIFT and GIFT-derived strains did not outperform non-GIFT strains, but 50% of all farmed tilapia in the country was of GIFT origin. Uncertainty over tilapia strains may be a contributing factor in decision-making when farmers purchase seed from hatcheries. Due to a lack of hatchery and farm traceability, there are significant uncertainties of tilapia genetics throughout Bangladesh, a similar situation to that described in the Philippines by Pemsl et al. (2008). Further research on strain preference in Bangladesh is required to effectively scale GIFT adoption. Assessing various tilapia farmer perceptions and farming behaviours will help to determine whether genetically improved tilapia is seen as lucrative to poor and rich farmers alike. Additionally, understanding tilapia perceptions and preferences at producer and consumer level can be useful for future tilapia selective breeding programmes (Murphy et al., 2020; Omasaki et al., 2016).

Shikuku et al. (2021) and Tran et al. (2021) discuss the requirements and potential positive impacts of scaling GIFT production in Bangladesh. Shikuku et al. (2021) found limited knowledge of improved strains and limited access to credit were major constraints in the dissemination and scaling of GIFT. Although GIFT may be more productive (Trinh et al., 2021) and profitable (Tran et al., 2021), production increases should not be prioritized during development attempts (Woltering et al., 2019). Scaling technology such as GIFT requires an approach which is inclusive and reflects the targets of the UNs Sustainable Development Goals (United Nations, 2015). Efforts to increase GIFT adoption and production in Bangladesh should focus on improving producer livelihoods and promoting sustainable, nutrition-sensitive food systems (Gómez & Ricketts, 2013; Ingram & Zurek, 2018; Tezzo et al., 2020).

Lewis (1997) suggested initiatives in Bangladesh aimed at improving the aquaculture sector did not focus on the resource poor but instead aimed at increasing production of expensive fish rather than improving food security and equity. More recently, Bogard et al. (2017) challenged the idea that increases in aquaculture production leads to improvements in food and nutrition security, since larger cultured species are less nutritive than small indigenous species in Bangladesh. Conversely, Toufique and Belton (2014) suggest poorer populations in Bangladesh are benefitting from aquaculture development as indirect linkages are more likely to produce poverty reducing results. It is argued that increases in fish consumption are an indicator of aquaculture's role in poverty reduction. This supports the idea that an increase in tilapia production may benefit poor consumers as the availability and affordability of tilapia increase. Prices of tilapia would likely fall due to market supply increases, and therefore benefitting poorer consumers. However, in consequence, poorer farmers would be more affected by farm-gate price decreases than better-off farmers.

In conclusion, GIFT juveniles outperformed the LS juveniles at both the early and advanced fry nursing stage. Farmer perceptions of GIFT seed suggests most farmers consider GIFT valuable; however, there may be differences of opinion between and within farmer well-being categories. It is clear from the results of this study GIFT can yield higher productivity and is more profitable when compared with other strains. In addition, improved tilapia strains may have reduced impacts on the environment as they grow faster and have better feed conversion rates. Therefore, promoting the use of improved strains and best management practices at hatchery and farm level should be considered during efforts in developing and improving the aquaculture sector in Bangladesh. To ensure farmers from all socioeconomic backgrounds can benefit from this technology, farmer training and better access to credit should be prioritized. Future research should consider the performance of a variety of improved and traditional strains over a broader geographical scale and assess farmer and consumer perceptions of tilapia.

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AUTHOR CONTRIBUTION

S. Horn- study design, data analysis and interpretation, writing of manuscript. M. Haque- study design, writing of manuscript. B. Barman- Study design, writing of manuscript. D. Little- study design, data analysis, writing of manuscript.

CONFLICT OF 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.

ETHICAL APPROVAL

The authors confirm that the ethical policies of the journal, as noted on the journal's author guidelines page, have been adhered to and the appropriate ethical review committee approval has been received.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author, SH. The data are not publicly available for participant privacy.

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