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Growth, yield and profitability of genetically improved farmed tilapia (GIFT) and non-GIFT strains in Bangladesh

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ABSTRACT

On-farm performance of the genetically improved farmed tilapia (GIFT) strain in monoculture and polyculture ponds in Bangladesh was assessed using a stratified random sample of 213 GIFT and 256 non-GIFT farmers. The GIFT strain of Nile tilapia (Oreochromis niloticus) was mostly farmed by small-scale farmers operating less than one ha of ponds and with a lower assets index than their non-GIFT counterparts. The GIFT strain had a faster growth rate (27% and 36% faster than that of non-GIFT tilapia in monoculture and polyculture, respectively). Although GIFT and non-GIFT farmers applied different stocking strategies with GIFT farmers growing much smaller fingerlings compared to non-GIFT farmers (7.3 g for GIFT and 17.2 g for non-GIFT, and 9.1 g for GIFT and 20.3 g for non-GIFT in monoculture and polyculture, respectively. Yields were statistically different between both strains in monoculture and polyculture (8.1 tons/ha per cycle for GIFT and 6.2 tons/ha per cycle for non-GIFT in monoculture, and 9.3 tons/ha per cycle for GIFT and 7.8 tons/ha per cycle for non-GIFT in polyculture). In polyculture systems, overall polyculture yield was statistically different at the 10% level (12.7 and 10.2 tons/ha for GIFT and non-GIFT ponds). In terms of profitability performance, GIFT tilapia is more profitable and cost-effective than non-GIFT. Findings from this study highlight the importance of adopting culture of high-performance strains to close yield gaps and realize the potential benefits of the GIFT strain.

1. Introduction

Aquaculture growth is critical to meet the globally increasing demand for fish, which is driven by rapid population growth, rising income and consumer preferences shifting towards healthier and more nutritious foods. However, aquaculture production of most of the 600 aquatic species farmed currently is still based largely on unimproved species, which are genetically similar to wild counterparts, with low production efficiency (Ponzoni et al., 2007; FAO, 2019). The use of genetically improved farmed fish strains can play an important role in meeting the growing demand for fish by increasing production gains (Acosta and Gupta, 2010; Olesen et al., 2015; Gjedrem and Rye, 2018), improving disease resistance (Houston, 2017; Barría et al., 2020; Kjetså et al., 2020) and enhancing socio-economic and welfare performance of the related aquaculture systems (Dey, 2000; Asian Development Bank, 2005). Despite these potential benefits, sound data on the actual performance of genetically improved strains of fish in farming systems is limited particularly in developing countries. The lack of benchmarking information is a likely contributing factor limiting consistent and sound investment into genetic improvement programs in aquaculture. The restriction of investment ultimately represents an impediment to the sustainable development of the aquaculture sector, particularly in developing countries where it is most needed to improve food and nutrition security, incomes, and livelihoods.

Our case study focused on Nile tilapia, which has emerged as one of the most important aquaculture fish, traded globally and farmed in more than 125 countries in the World (El-Sayed, 2020). In 2018, there were more than 5.5 million metric tons of farmed tilapia produced globally, with Nile tilapia (*Oreochromis niloticus*) ranking third in terms of total global fish production (FAO, 2018). The success of global tilapia is in

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part related to the establishment of selective genetic breeding programs for the species initially through the development of Genetically Improved Farmed Tilapia (GIFT) technology by WorldFish (formerly, International Center for Living Aquatic Resources Management, ICLARM) and partners over thirty years ago (Silva and Davy, 2010; Kumar and Engle, 2016). GIFT technology has contributed to the rapid growth of the tilapia industry worldwide since 2001 (Kumar and Engle, 2016).

Previous studies suggested that the dissemination and adoption of GIFT help to: (1) increase fish yields (Dey et al., 2000; Ponzoni et al., 2007) which improve economic returns for the farmer (Khaw et al., 2008; Haque et al., 2016); (2) increase survival rate (Khaw et al., 2008), shorten harvest time and yield higher individual harvesting weight (Dey et al., 2000; Haque et al., 2016); (3) reduce production and operational costs (Dey et al., 2000); (4) reduce local fish market prices improving affordability particularly for low income consumers (Dey, 2000; Yosef, 2009); and (5) generate rural employment and income (Asian Development Bank, 2005). These studies mostly used data from on-station research or on-farm trials (Dey et al., 2000; Asian Development Bank, 2005; Khaw et al., 2008; Haque et al., 2016).

Despite these contributions, it is evident that there has been no rigorous investigation of performance of GIFT tilapia in real farming contexts in developing countries. A systematic review of yield gap[1] in tilapia farming found only 26 studies providing information on basic production parameters (Mengistu et al., 2019), but few with economic analysis (Omasaki et al., 2017). The absence of information on actual performance of GIFT makes it difficult to assess critical yield gaps and identify effective strategies and interventions required to address them. The lack of sound cost benefit analysis related to the use of different inputs or practices prevents more accurate business planning and the assessment of tradeoffs. Reliable data on the current on-farm performance of tilapia is imperative for the industry and governments to design appropriate strategies and effective policies for future investment in aquaculture development.

The overall objective of this study was thus to assess the on-farm performance of the latest GIFT strain introduced for grow-out tilapia aquaculture with that of existing non-GIFT strains used in Bangladesh where GIFT tilapia is well established. Bangladesh was chosen for this study because GIFT has been introduced several times from 1994 (Hussain et al., 2000) to 2012 (Keus et al., 2017) along with other strains (Ponzoni et al., 2011;Hussain et al., 2013). The 18-fold increase in tilapia production in Bangladesh from 19,320 MT in 2005 to 347,800 MT in 2015 (FAO, 2018) has been attributed in large part to GIFT and placed the country in the third rank, after China and Indonesia, among the top tilapia producing countries in the Asia-Pacific region (FAO, 2016). Specific objectives of the study were to assess the current growth, yield and profitability of GIFT and non-GIFT strains in Bangladesh using data generated through a recall tilapia farm survey.

2. Materials and methods

2.1. Study population and sampling strategy

The population of interest in this study comprised tilapia farming households in Bangladesh. A stratified sampling strategy was used to select a random sample of GIFT and non-GIFT farmers (Fig. 1). A pre-existing list of tilapia hatcheries in Bangladesh, organized by district and the strain produced, was obtained from WorldFish office in Bangladesh. Based on this list, an initial survey was conducted to identify the hatcheries that were still in operation and group them into two branches of tilapia seed dissemination. The first branch (GIFT) which is the focus of this study, comprised eight nucleus breeding hatcheries that received brood-stock of GIFT from Jitra in Malaysia in 2012 and multiplication hatcheries that received GIFT broodstock from the above eight hatcheries. The second branch (non-GIFT) comprised non-GIFT hatcheries, producing Chitralada, Genomar and FaST tilapia strains. The Chitralada strain of Nile tilapia was introduced to Bangladesh from Thailand in 1974 and later was reintroduced in 1987 (also from Thailand) and managed by the Bangladesh Fisheries Research Institute (BFRI). Other tilapia strains such as Genomar and FaST have been introduced by private sector hatcheries and entrepreneurs from the Philippines (Hussain et al., 2013). Due to the limited sample size, which does not allow us to have the required statistical power for a head to head comparison of GIFT with other strains, we adopted the GIFT and non-GIFT dichotomy for comparison in our study design.

During the hatcheries review and grouping, we found that some hatcheries produced both GIFT and non-GIFT strains and others produced both the latest and earlier strains of GIFT. Those hatcheries did not necessarily have lists for buyers of the different strains they produced. In order to prevent bias and minimize measurement error caused by strain misclassification—e.g. mixing data from different strains—such hatcheries were not sampled. Following this approach, hatcheries from 14 districts were selected for inclusion in the study and categorized into five clusters as follows: (C1) South west including Jessore, Khulna, Satkhira, Narail; (C2) South including Bhola, Patuakhali; (C3) South east including Comilla, Chandpur, Noakhali; (C4) North center including Mymensingh and Sherpur; and (C5) North west including Rangpur, Dinajpur, and Gaibandha. In each cluster, hatcheries were randomly selected using probability proportionate-to-size sampling, making a total of 53 hatcheries included in the study.

A team of enumerators visited the selected hatcheries to generate complete lists of tilapia fish farmers to whom fingerlings were sold in 2018. The decision to collect the lists from hatcheries (the source of the fish seed) was informed by farmers' limited knowledge about the strains they grow. Using the generated lists of tilapia fish farmers, we employed probability proportionate-to-size sampling to randomly select farmers for interviews. The final sample comprised 473 farmers (Fig. 1) who had completely harvested a GIFT or non-GIFT tilapia crop in 2018. Due to inconsistencies and incompleteness in four observations, the sample size was reduced to 469 farm households.

2.2. Data collection and analysis

Data were collected through personal interviews from December 2018 to February 2019, using a predesigned questionnaire in Open Data Kit (ODK). The survey comprised the following modules: (1) farming household characteristics; (2) aquaculture production and marketing activities including input use and cost as well as output harvested and sold; (3) access to information and financial services; (4) risk preference and behavior; and (5) assets ownership. Data on aquaculture production were collected at pond level. We included all ponds that were used for tilapia production under both monoculture and polyculture, but excluded ponds that were not stocked with tilapia. The survey captured detailed data about all types of aquaculture production practices allowing us to characterize the aquaculture production systems. A training workshop on the survey tool was carried in December 2018 in Bangladesh. In total, 17 enumerators and four supervisors from Development Research Initiative (dRi) in Bangladesh were trained in administering the survey. The survey tool was pretested and updated accordingly during the weeklong training when the survey was piloted.

[1] Mengistu et al., 2019 define yield gaps as the difference in productivity between the best performing farms and low performing farms. More specifically Zhengfei et al. (2006) identify three production levels: potential, attainable, and actual level. "The potential yield level is the highest production level achievable with the given physical environment and genetic characteristics and assuming no growth limiting and growth-reducing factors. Attainable yield is when growth limiting factors occur. The attainable yield level assumes no growth-reducing factors. Growth-reducing factors lower the production level further to the actual yield level." In this study, we will adopt this definition for aquaculture systems.

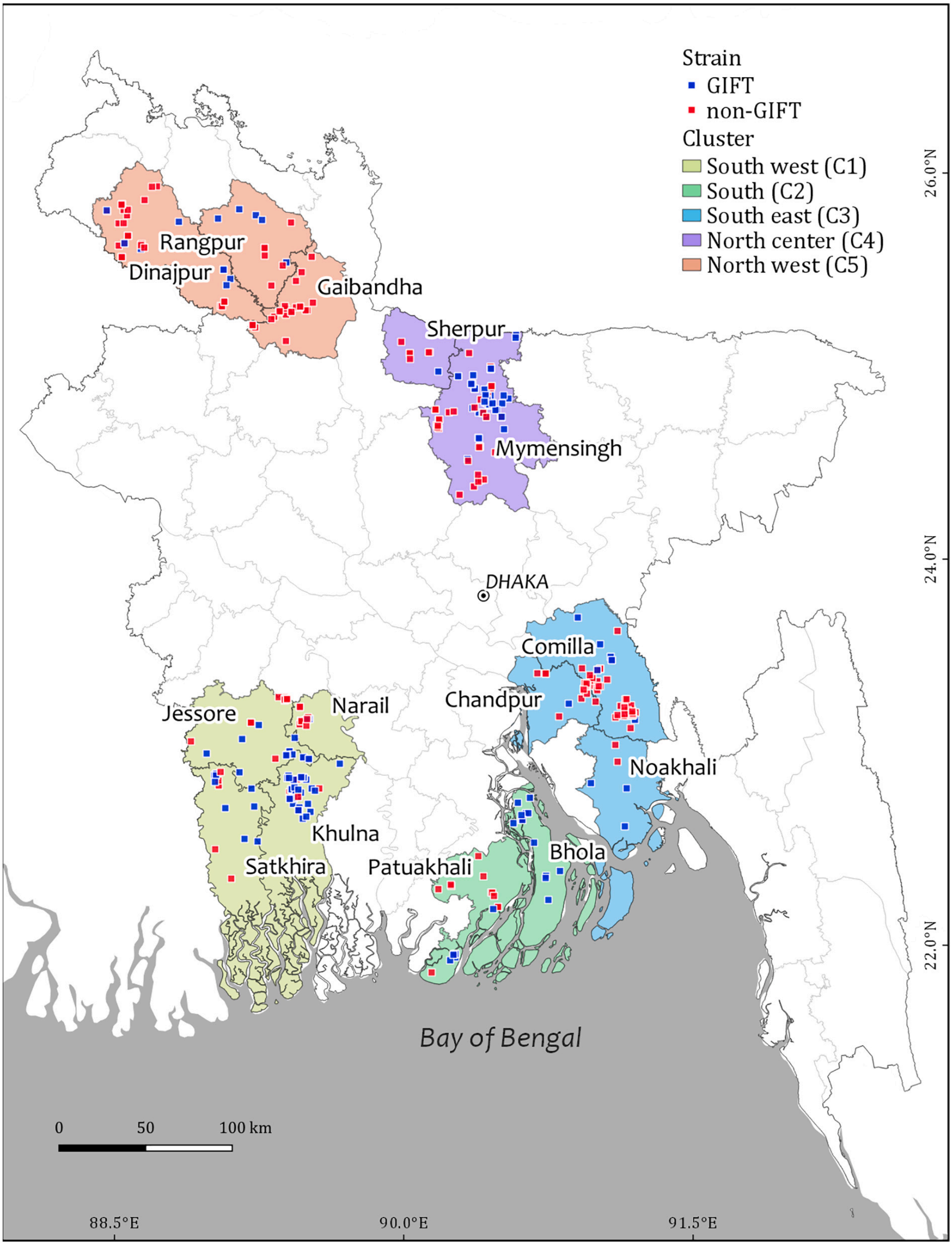

Fig. 1. Map of surveyed households.

During the survey, a research analyst at WorldFish was assigned to daily download the data, check, and provide timely feedback for any potential mistakes and inconsistencies. Field supervisors and enumerators were thus informed and asked to address the inconsistencies.

Descriptive and comparative analysis were used to characterize and assess performance of tilapia aquaculture systems in Bangladesh. Comparative analysis included Benefit-Cost analysis (BCA) to assess the profitability and cost-effectiveness of GIFT and non-GIFT tilapia aquaculture in monoculture and polyculture systems. Tilapia revenue was computed as yield of tilapia harvested (kg/ha per cycle) multiplied by the selling price (USD) for a kg of tilapia. The inputs included two growth inputs: fingerlings and feed, and four facilitating inputs: labor, fertilizer, capital, and other chemicals (e.g., water treatment chemicals). The inputs were measured in USD/ha per cycle using the World Bank's 2018 official exchange rate for Bangladesh. Labor cost was calculated as follows. First, we considered three types of labor, namely family, hired part-time, and hired full-time. For each type of labour, male and female person days were computed. Cost for hired labor was obtained by multiplying the total number of person days by the median daily wage for the specific type of labor. Cost for family labour was computed as an opportunity cost assuming a daily wage equal to 75% of the wage for hired full-time labor. We further included other costs such as renting of land, electricity, ice, transportation, fuel, and miscellaneous expenses such as cost of ropes, tubes, batteries, and torches. We calculated gross margins as total revenue less total variable cost of production. In addition, we computed the benefit-cost ratio (BCR) as total revenue divided by total variable cost.

In addition to profitability analysis, we assessed biological performance of GIFT and non-GIFT tilapia culture based on growth rate, size at both stocking and harvest, survival rate, and feed conversion ratio. Analysis of these variables is important because they influence productivity and cost of production hence determining profitability. We measured tilapia specific growth rate (SGR) in percent per day following Eq. (1), where W_t and W_i are tilapia weights at harvest and stocking respectively and t is crop duration in number of stocking days (Lugert et al., 2016). To measure survival (%), the number of tilapia harvested was divided by the number of tilapia stocked. The resulting number was multiplied by 100 to express as a percentage. Finally, feed conversion ratio (FCR) was measured by dividing total quantity of feed (kg) by quantity of harvested fish (kg).

$$SGR = \frac{Log(Wt) - Log(Wi)}{t} * 100 \quad (1)$$

Differences in socioeconomic characteristics and performance between GIFT and non-GIFT farmers were assessed descriptively using independent sample *t*-tests. However, ratios such as FCR and BCR do not usually show normal distributions (as is the case in this study—see Fig. 2). We, therefore, also performed non-parametric Mann-Whitney test to assess statistical significance of observed differences in FCR and BCR between GIFT and non-GIFT farmers. In addition, we compared performance between monoculture and polyculture systems focusing on five species commonly cultured with tilapia, namely Rohu *(Labeo rohita)*, Catla *(Catla catla)*, Silver carp (*Hypophthalmichthys molitrix*), Mrigal *(Cirrhinus mrigala)*, and Pangasius (*Pangasius hypophthalmus*). This level of disaggregated analysis, looking at the specific species that were cultured together with tilapia, allows us to assess whether or not tilapia production affects production of other species in a polyculture system.

2.3. Propensity score matching

In addition to descriptive analysis, the causal performance of GIFT in monoculture and polyculture systems was estimated by the average treatment effect on the treated (ATT), defined as the average difference in outcomes of tilapia farming households, with and without the GIFT strain (Takahashi and Barrett, 2013):

$$\text{ATT} = E\{Y_{iA} - Y_{iN} | T_i = 1\}$$

$$\text{ATT} = E(Y_{iA} | T_i = 1) - E(Y_{iN} | T_i = 1) \quad (1)$$

where $E\{\cdot\}$ is the expectation operator, Y_{iA} is the potential outcome under GIFT strain adoption while Y_{iN} is the potential outcome under no adoption of GIFT and T_i is the treatment indicator, equal to one if the household farmed GIFT and zero if otherwise. The challenge in Eq. (1) is that it is not possible to observe, for the same GIFT farming household i, the counterfactual outcome, $E(Y_{iN}| T_i = 1)$, (that is, the potential outcome had the household not farmed GIFT). Replacing the unobserved counterfactuals with the outcomes of non-GIFT farmers, $E(Y_{iN}| T_i = 0)$, may result in biased ATT estimates (Angrist and Pischke, 2009).

In this study, propensity score matching (PSM) estimation method was used as the primary estimator in order to avoid the problem described above. PSM is based on the assumption that sample selection bias can be eliminated by conditioning on observable variables. This is achieved by matching each GIFT farming household with one or more non-GIFT farming households with similar observable characteristics. Therefore, matching models simulate the conditions of an experiment in which GIFT and non-GIFT farming households are randomly assigned, allowing for the identification of a causal link between strain choice and measures of performance. Two assumptions are crucial when applying

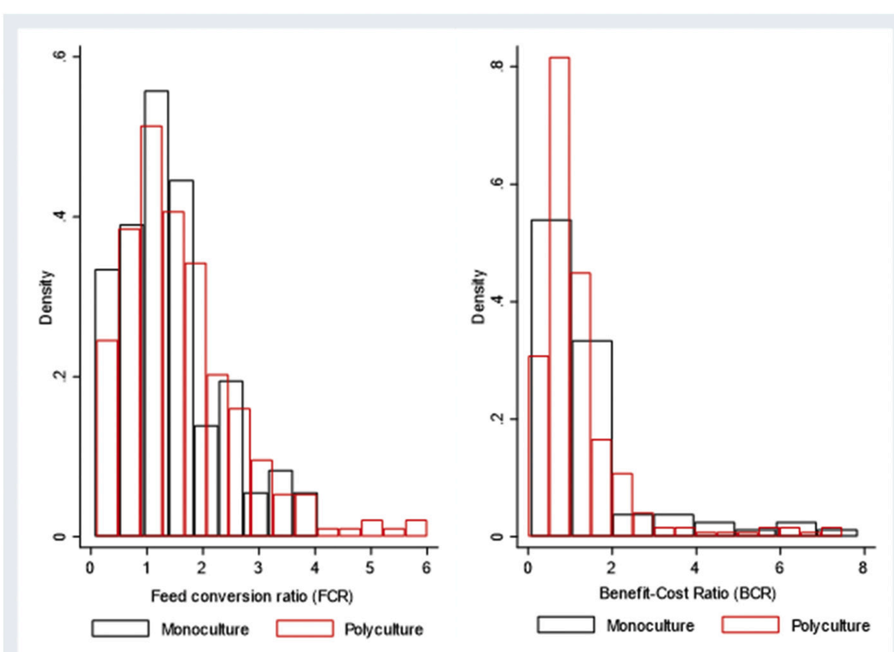

Fig. 2. Histogram of feed conversion ratio (FCR) and benefit-cost ratio.

PSM, namely unconfoundedness assumption also referred to as conditional independence assumption (CIA) and common support assumption (CSA). The CIA implies that once a vector of observable characteristics is controlled for, adoption of GIFT will be random and uncorrelated with the outcome variables. The propensity score under the CIA is given by:

$$p(W) = pr(T = 1|W) = E(T|W) \tag{2}$$

where $T = 1$ or 0 is the indicator for adoption of GIFT or otherwise, and W is the vector of observable characteristics. The conditional distribution of W, given $p(W)$, is similar in both groups of GIFT and non-GIFT farmers. On the other hand, the CSA helps in ensuring that every individual has a positive probability of being either a GIFT or a non-GIFT farmer, hence ruling out perfect predictability. The CSA is expressed as:

$$0 < pr(T = 1|W) < 1 \tag{3}$$

Under the assumptions (2) and (3), the ATT can be expressed as follows:

$$\text{ATT} = E[E\{Y_{iA}|T_i = 1,p(W)\} - E\{Y_{iN}|T_i = 0,p(W)\}|T = 1] \tag{4}$$

One of the weaknesses of the PSM method is that it does not capture selection bias based on unobserved heterogeneity. However, Rosenbaum bounds sensitivity analysis can check if the PSM results are sensitive to hidden bias (Becker and Andrea, 2002).

The PSM approach as applied in this study followed two steps. The first step involved estimation of the propensity scores or the conditional probability of farming GIFT using a probit model. In the second step, GIFT and non-GIFT farmers were matched by their estimated propensity scores using the nearest neighbour matching algorithm. Nearest neighbour matching matches a subject from the control group to a subject in the treatment group, based on the closest propensity score. We also conducted robustness checks in which we used two other matching algorithms, namely kernel-based matching and radius matching. Our results remain robust to different matching algorithms. Results of the other matching algorithms are available from the authors upon request.

Propensity score matching helps to balance the distribution of observed covariates (Lee, 2008), meaning there should be no systematic differences in the distribution and overlap of covariates between GIFT and non-GIFT farming households after matching (Gitonga et al., 2013). The quality of matching can, therefore, be tested using covariates balancing tests (Rosenbaum and Rubin, 1985; Sianesi, 2004). Specifically, the equality of means of observed characteristics in the GIFT and non-GIFT groups after matching was examined using a two-sample *t*-test: after matching, there should be no significant differences (Gitonga et al., 2013). Further, the matching was tested by comparing the pseudo R^2 and *p*-values of the likelihood ratio test of the joint insignificance of all the regressors obtained from the probit analysis before and after matching the samples. The pseudo-R^2 should be lower and the joint significance of covariates should be rejected (Sianesi, 2004; Kassie et al., 2011). Finally, a propensity score graph was used to check visually if the common support condition was satisfied, that is, if there was sufficient overlap. In addition, the balancing property was checked using mean absolute standardized bias (MASB) between GIFT and non-GIFT farmers as suggested by Rosenbaum and Rubin (1985); a standardized difference greater than 20% should be considered too large and an indicator that the matching process has failed. The PSM estimation is not robust in the presence of hidden bias or selection on unobservables. Using the Rosenbaum (2002) bounds test, we checked the sensitivity of the estimated average adoption effects to hidden bias.

The observable covariates considered, i.e. factors that were likely to affect the probability of farming GIFT, were selected based on previous adoption and impact studies and economic theory (e.g., Kassie et al., 2011; Shikuku et al., 2019), and included farmer and household characteristics (age, education, assets index, number of household members involved in aquaculture, whether aquaculture is the main source of livelihoods for the household, farmer's experience in tilapia farming, access to information, access to credit, and risk attitude). The estimation further controlled for biological factors of stocking density, survival rate and weight at stocking.

3. Results

3.1. Socioeconomic characteristics of sample respondents

Descriptive statistics of GIFT and non-GIFT households practicing tilapia monoculture (Table 1) showed no significant differences in most socioeconomic characteristics, such as education, age, degree of risk aversion, and experience in tilapia farming of respondent, access to credit, and size of land under aquaculture ($p > 0.1$). However, households practicing GIFT monoculture had a lower assets index relative to non-GIFT farmers ($p < 0.01$) and also had smaller household size ($p < 0.1$). GIFT and non-GIFT households engaging in polyculture had similar characteristics in terms of age, experience in tilapia farming, access to credit, and household size. However, the proportion of respondents completing education above class 10 was significantly higher for non-GIFT than GIFT farmers ($p < 0.05$). Similarly, GIFT farmers were more risk averse, had a smaller endowment of assets, and owned smaller sizes of agriculture and aquaculture land than non-GIFT farming households ($p < 0.01$). For both GIFT and non-GIFT households, polyculture farming was commonly practiced. Of 469 tilapia farming households included in the study, 388 of them (83%) farmed tilapia in polyculture with other fishes (Table 1).

3.2. Bio-technical characteristics and performance of tilapia farming

GIFT households had smaller ponds than non-GIFT households under both monoculture and polyculture but the difference was statistically significant only for polyculture systems ($p < 0.01$) (Table 2). Tilapia stocking densities were significantly higher for GIFT (~4 fish per m^2) than non-GIFT (~3 fish per m^2) in both monoculture and polyculture systems ($p < 0.01$). Specifically, the stocking density for GIFT ponds was 28% higher than that for non-GIFT ponds in monoculture and 33% higher in polyculture. The mean weight of individual fish stocked by GIFT households, in both monoculture (7.3 g) and polyculture systems (9.1 g) was significantly lower than non-GIFT households for both monoculture (17.2 g) and polyculture (20.3 g)—less than half of that for non-GIFT under both culture systems ($p < 0.01$). Stocking weights were 15–20% less for both tilapia types in monoculture than in polyculture. Those households who practiced polyculture stocked with similar stocking densities as those of monoculture farmers (~4 to 5 fish per m^2) and also added other species such as Indian carps (Rohu, Mrigal and Catla), and Chinese carps (Silver carp). A small number of households also stocked Pangasius catfish in their tilapia polyculture ponds.

Tilapia culture duration averaged at 159 to 164 days (around 5.5 months) in monoculture which was shorter than that in polyculture which took about 172 days (around 6 months) to complete the cycle. Culture duration was not statistically different between GIFT and non-GIFT ponds for both monoculture and polyculture systems (Table 2).

GIFT households harvested fish at a significantly smaller average size, 258 g in monoculture and 309 g in polyculture, than non-GIFT households who harvested fish at 393 g in monoculture to 413 g in polyculture systems ($p < 0.01$) (Table 2). On average, survival rates of GIFT and non-GIFT was similar in monoculture (75% and 78%). Survival rates were 73% to 87%, respectively in polyculture ponds, 19% higher for non-GIFT ($p < 0.01$) (Table 2).

The specific growth rate was significantly higher for GIFT than non-GIFT tilapia in both monoculture and polyculture systems ($p < 0.01$). In monoculture and polyculture systems, GIFT tilapia grew at 3.3% and 3.0% per day, respectively, 27% and 36% faster than non-GIFT tilapia whose growth rates were 2.6% to 2.2% per day respectively (Table 2). Mean feed conversion ratio (FCR) averaged 1.5 and 2.1 in monoculture and 2.0 and 2.2 in polyculture for GIFT and non-GIFT, respectively, but

Table 1
Mean and standard errors (S.E.) of the characteristics of the households and sample respondents of monoculture and polyculture farms.

	Monoculture							Polyculture						
	GIFT			Non-GIFT				GIFT			Non-GIFT			
Variable	Mean		S.E.	Mean		S.E.	p-value	Mean		S.E.	Mean		S.E.	p-value
Education (1 = respondent's education > class X)	0.7	±	0.1	0.6	±	0.1	0.34	**0.5**	**±**	**0.0**	**0.6**	**±**	**0.0**	**0.05**
Age (years)	39.2	±	1.4	36.5	±	1.8	0.12	39.5	±	0.8	38.6	±	1.0	0.24
Risk aversion (scores)	14.2	±	1.5	14.7	±	1.7	0.41	**15.8**	**±**	**0.7**	**13.2**	**±**	**0.9**	**0.01**
Asset index (scores)	**1.6**	**±**	**0.1**	**2.0**	**±**	**0.1**	**0.00**	**1.8**	**±**	**0.1**	**2.1**	**±**	**0.1**	**0.00**
Experience in tilapia farming (years)	4.5	±	0.9	3.8	±	0.5	0.25	5.3	±	0.4	5.2	±	0.4	0.44
Access to credit (1 = yes; 0 = otherwise)	0.2	±	0.1	0.2	±	0.1	0.23	*0.2*	±	*0.0*	*0.2*	±	*0.0*	*0.09*
Size of households (persons)	*5.1*	±	*0.3*	*5.7*	±	*0.4*	*0.09*	5.9	±	0.3	5.7	±	0.2	0.29
Total size of land owned (ha)	1.6	±	0.2	1.9	±	0.3	0.19	**2.0**	**±**	**0.1**	**2.6**	**±**	**0.2**	**0.01**
Size of land under aquaculture (ha)	0.8	±	0.1	1.0	±	0.1	0.14	**1.0**	**±**	**0.1**	**1.4**	**±**	**0.1**	**0.00**
Observations (no. of households)	46			35				167			221			

Note: Significant differences between GIFT and non-GIFT farmers at p < 0.05 are given in bold and P < 0.10 (but >0.05) are given in italics.

Table 2
Mean and standard errors (S.E.) of the technical characteristics of GIFT and non-GIFT monoculture and polyculture systems.

	Monoculture							Polyculture						
	GIFT			Non-GIFT				GIFT			Non-GIFT			
Variable	Mean		S.E.	Mean		S.E.	p-value	Mean		S.E.	Mean		S.E.	p-value
Size of aquaculture ponds (ha)	0.3	±	0.0	0.4	±	0.1	0.15	**0.4**	**±**	**0.0**	**0.5**	**±**	**0.0**	**0.00**
Tilapia														
Stocking density (pieces m^{-2})	**4.6**	**±**	**0.4**	**3.3**	**±**	**0.1**	**0.02**	**4.2**	**±**	**0.2**	**2.8**	**±**	**0.1**	**0.00**
Weight at stocking (g)	**7.3**	**±**	**1.6**	**17.2**	**±**	**1.6**	**0.00**	**9.1**	**±**	**1.3**	**20.3**	**±**	**1.3**	**0.00**
Crop time (no. of growing days)	164.2	±	6.1	159.3	±	5.4	0.27	171.9	±	3.8	172.3	±	3.6	0.47
Specific growth rate (%/day)	**3.3**	**±**	**0.2**	**2.6**	**±**	**0.1**	**0.00**	**3.0**	**±**	**0.1**	**2.2**	**±**	**0.1**	**0.00**
Weight at harvesting (g)	**257.7**	**±**	**13.2**	**393.2**	**±**	**17.8**	**0.00**	**308.5**	**±**	**8.4**	**413.2**	**±**	**10.2**	**0.00**
Survival (%)	75	±	3.0	78	±	3.0	0.27	**73**	**±**	**2.0**	**87**	**±**	**1.0**	**0.00**
Feed conversion ratio (FCR)	*1.50*	±	*0.14*	*2.12*	±	*0.43*	*0.09*	1.97	±	0.16	2.22	±	0.20	0.17
Polyculture feed conversion ratio (FCR)								1.28	±	0.07	1.39	±	0.08	0.16
Polyculture stocking density (pieces m^2)														
Rohu								*0.3*	±	*0.1*	*0.1*	±	*0.0*	*0.06*
Catla								*0.1*	±	*0.0*	*0.0*	±	*0.0*	*0.08*
Silver carp								**0.1**	±	**0.0**	**0.1**	±	**0.0**	**0.02**
Mrigal								**0.1**	**±**	**0.0**	**0.1**	**±**	**0.0**	**0.01**
Pangasius								**1.5**	**±**	**0.4**	**0.7**	**±**	**0.1**	**0.01**
Observations (ponds)	82			82				245			228			

Notes: Sample sizes (numbers of ponds) for stocking density of different species grown with GIFT and non-GIFT respectively were 225 and 215 for rohu, 137 and 136 for catla, 144 and 136 for silver carp, 136 and 180 for mrigal and 22 and 30 for Pangasius. Significant differences between GIFT and non-GIFT farmers at p < 0.05 are given in bold and P < 0.10 (but >0.05) are given in italics.

the differences were not statistically significant at the 5% significance level ($p > 0.08$) (Table 2). Results of the non-parametric Mann-Whitney test also confirmed that differences in FCR between GIFT and non-GIFT farmers were not statistically significant in both monoculture ($p > 0.09$) and polyculture ($p > 0.10$). The higher growth rate of GIFT compared to non-GIFT was likely due to the smaller size at stocking of GIFT fish compared to non-GIFT fish.

3.3. Yield and profitability of tilapia farming

Before turning to the causal performance of GIFT farming, it is pertinent to discuss the quality of the matching process, results for which are presented in the Appendix Tables A1-A4 and Fig. A1. After matching, there were no significant differences in observable covariates between GIFT and non-GIFT farmers practicing monoculture (Table A1). In polyculture, the magnitude of the differences was much reduced relative to that before matching and only three variables revealed significant differences at $p < 0.05$ (Table A2). Bias was substantially reduced after matching for both monoculture and polyculture. The distribution of the estimated propensity scores by type of strain farmed under different farming systems demonstrated the common support assumption was satisfied (Fig. A1).

The standardized mean difference for overall covariates used in the propensity score (around 29.2% for monoculture and 39.1% for polyculture before matching) was reduced to 15.2% and 12.2% for monoculture and polyculture, respectively after matching (Table A3). The *p*-values of the likelihood ratio tests indicated that the joint significance of covariates was rejected after matching in monoculture. The pseudo-R^2 also dropped significantly from 23 to 31% before matching to 0.05–0.06% after matching. Therefore, the low pseudo-R^2, low mean standardized bias, high total bias reduction, and the non-significant *p*-values of the likelihood ratio test after matching suggest that the proposed specification of the propensity score was successful in terms of balancing the distribution of covariates between the GIFT and non-GIFT farmers, especially under monoculture.

Results of the Rosenbaum bounds sensitivity analysis on hidden bias are presented in Table A4. The higher the value of Γ the greater confidence GIFT and non-GIFT perform differently. The critical value of gamma, Γ (below which the conclusion of better performance of GIFT compared with non-GIFT would be questioned) is in the range of 1.1–3.4 (both in monoculture and polyculture). These results are very close to those reported by studies examining impacts of agricultural innovations and indicate the absence of substantial hidden bias (Kassie et al., 2011; Ogutu et al., 2014).

The propensity score matching analysis confirmed GIFT had a faster specific growth rate than non-GIFT in both monoculture and polyculture systems, with 3.3% and 3.1% body weight per day for GIFT and 2.6% and 2.4% body weight per day for non-GIFT in monoculture and polyculture, respectively (Table 3). Mean feed conversion ratio for GIFT remained the same as the results we reported in Table 2 (FCR 1.5 and 2.0 in monoculture and polyculture). However, FCR for non-GIFT has changed and FCR between GIFT and non-GIFT ponds in polyculture systems (2.0 versus 3.1) was statistically different at the 5% level. Average yield of tilapia between GIFT and non-GIFT ponds in monoculture was statistically different ($p < 0.01$) with 8.1 and 6.2 metric tons/ha produced per cycle, respectively (Table 3). In polyculture systems, average fish yield of GIFT and non-GIFT households was statistically different at the 10% level ($p < 0.1$) with 12.7 and 10.2 metric tons/ha produced per cycle, respectively (Table 3).

The average selling price of GIFT tilapia (1.2 USD per kg) was significantly less than that of non-GIFT tilapia (1.4 USD per kg) in monoculture systems but was not different in polyculture systems (Table 3). The difference in selling price is plausible given that mean individual body weight at harvest was less for GIFT than non-GIFT tilapia.

Gross revenue from GIFT and non-GIFT ponds was estimated at 9,900 USD and 8,600 USD/ha per cycle respectively in monoculture and 17,400 USD and 13,200 USD/ha per cycle respectively in polyculture, i.e. 1,300 USD higher for GIFT households ($p < 0.1$) under monoculture and 4,200 USD higher for GIFT households ($p < 0.05$) under polyculture (Table 3).

Average variable production costs, estimated at 8,000 USD and 8,800 USD/ha per cycle for GIFT and non-GIFT ponds, respectively under monoculture and at 11,400 USD and 11,400 USD/ha per cycle, respectively under polyculture (Table 3), were significantly lower for GIFT ($p < 0.1$) in monoculture systems but were not different in polyculture systems.

Average gross profit in tilapia monoculture was statistically different at the 5% level ($p < 0.05$) with 1,930 USD and − 260 USD/ha per cycle for GIFT and non-GIFT ponds, respectively. Combined gross profits of tilapia and other fishes in polyculture systems were also different at the 5% level ($p < 0.05$) with 5,990 USD and 1,820 USD/ha per cycle, respectively (Table 3).

Benefit-cost ratio (BCR) overall for monoculture ponds was significantly different ($p < 0.01$) at 1.7 and 1.1 for GIFT and non-GIFT farmers, respectively, a result of the significant difference between the average yield (Table 3). In polyculture, there was significant difference in BCR at the 10% level ($p < 0.1$), with 2.0 and 1.5 for GIFT and non-GIFT ponds respectively.

Table 4
Mean of outcome variables of GIFT and non-GIFT tilapia in polyculture systems, and the mean and standard error (in parenthesis) of the average treatment effects (ATT) using propensity score matching (nearest neighbour matching).

Outcome variables	GIFT	Non-GIFT	ATT	*p*-value
Average yield (metric tons/ha/per cycle)	**9.31**	**7.80**	**1.51 (0.72)**	**0.04**
Sale price ($US000/ton/cycle)	1.20	1.22	−0.02 (0.03)	0.58
Tilapia revenue ($US000/ha/cycle)	*11.29*	*9.55*	*1.74 (0.91)*	*0.06*
Production costs ($US000/ha/cycle)	10.44	10.96	−0.52 (1.22)	0.67
Gross profits ($US000/ha)	0.85	−0.82	1.67 (1.68)	0.32
Benefit-Cost Ratio (BCR)	**1.43**	**1.11**	**0.32 (0.16)**	**0.05**

Note: Significant differences between GIFT and non-GIFT farmers at p < 0.05 are given in bold and P < 0.10 (but >0.05) are given in italics.

For polyculture systems, when evaluating tilapia alone, yield was statistically different at the 5% level with 9.3 tons/ha per cycle and 7.8 tons/ha per cycle for GIFT and non-GIFT respectively (Table 4). Tilapia revenue and benefit cost ratio between GIFT and non-GIFT ponds were also statistically different at the 10% level and 5% level, respectively. Sale price, revenue, production cost, and gross profit of GIFT and non-GIFT households were not significantly different. These results suggested that difference in revenue and BCR of GIFT and non-GIFT is likely due to higher yield of GIFT than non-GIFT in polyculture systems.

Feed costs accounted for the major proportion (68% to 78%) of the total variable costs in both monoculture and polyculture, with 5,910 USD to 7,890 USD/ha per cycle in monoculture and 6,620 USD to 8,600 USD/ha per cycle for monoculture and polyculture ponds (Table 5). Feed cost was not significantly different between GIFT and non-GIFT ponds in both in monoculture and polyculture ponds. The second most important cost item that is seed cost, was lower for GIFT than non-GIFT in monoculture, but the difference was not significant (Table 5). These results suggested that lower production costs of GIFT compared to non-GIFT ponds reported in Table 3 were due to a combination of different input use and management practices (feed, seed, labor, etc) applied by GIFT and non-GIFT farmers.

4. Discussion

Our results showed that GIFT was mostly cultured by small-scale farmers in Bangladesh who had small sizes of land (less than one ha) available for aquaculture and low assets relative to those farmers who grew non-GIFT tilapia. Furthermore, the analysis showed that GIFT and non-GIFT households applied different stocking strategies with GIFT

Table 3
Mean of outcome variables of GIFT and non-GIFT monoculture and polyculture systems, and the mean and standard error (in parenthesis) of the average treatment effects (ATT) using propensity score matching (nearest neighbour matching).

	Monoculture				Polyculture			
Outcome variables	GIFT	Non-GIFT	ATT	*p*-value	GIFT	Non-GIFT	ATT	*p*-value
Specific growth rate (%/day)	**3.3**	**2.6**	**0.71 (0.30)**	**0.02**	**3.1**	**2.4**	**0.68 (0.16)**	**0.00**
Feed conversion ratio (FCR)	1.5	1.8	−0.29 (0.20)	0.15	**2.0**	**3.1**	**−1.10 (0.24)**	**0.00**
Average yield (metric tons/ha/per cycle)	**8.1**	**6.2**	**1.91 (0.54)**	**0.00**	*12.7*	*10.2*	*2.52 (1.44)*	*0.08*
Sale price ($US000/ton/cycle)	1.2	1.4	−0.16 (0.03)	0.00	1.20	1.2	−0.02 (0.03)	0.58
Revenue ($US000/ha/cycle)	*9.9*	*8.6*	*1.80 (0.70)*	*0.07*	**17.4**	**13.2**	**4.20 (1.90)**	**0.03**
Production costs ($US000/ha/cycle)	**8.0**	**8.8**	**−0.80 (0.40)**	**0.03**	11.4	11.4	−0.00 (1.28)	0.99
Gross profits ($US000/ha)	**1.9**	**−0.3**	**2.19 (0.93)**	**0.02**	**6.0**	**1.8**	**4.17 (1.95)**	**0.03**
Benefit-Cost Ratio (BCR)	**1.7**	**1.1**	**0.65 (0.21)**	**0.00**	*2.0*	*1.5*	*0.56 (0.33)*	*0.08*

Note: Significant differences between GIFT and non-GIFT farmers at p < 0.05 are given in bold and P < 0.10 (but >0.05) are given in italics.

Table 5
Mean of the cost composition of GIFT and non-GIFT monoculture and polyculture systems, and the mean and standard error (in parenthesis) of the average treatment effects (ATT) using propensity score matching (nearest neighbour matching).

	Monoculture				Polyculture			
Cost category (US$000/ha per cycle)	GIFT	Non-GIFT	ATT	*p*-value	GIFT	Non-GIFT	ATT	*p*-value
Feed cost	5.91	6.62	−0.71 (0.74)	0.34	7.89	8.60	−0.71 (0.72)	0.32
Seed cost	0.98	1.12	−0.14 (0.17)	0.41	**0.97**	**0.60**	**0.37 (0.12)**	**0.00**
Fertilizer cost	*0.04*	*0.03*	*0.01 (0.01)*	*0.08*	**0.07**	**0.04**	**0.03 (0.01)**	**0.00**
Labour cost	0.03	0.12	−0.09 (0.06)	0.10	0.46	0.48	−0.02 (0.12)	0.89
Cost of renting ponds	0.03	0.10	−0.07 (0.06)	0.27	0.40	0.52	−0.12 (0.09)	0.17
Other pond-specific cost	0.01	0.11	−0.10 (0.08)	0.20	0.28	0.28	0.00 (0.11)	0.99
Other non pond-specific cost	0.03	0.08	−0.05 (0.07)	0.44	0.37	0.30	0.07 (0.05)	0.17

Note: Significant differences between GIFT and non-GIFT farmers at $p < 0.05$ are given in bold and $P < 0.10$ (but >0.05) are given in italics.

farmers stocking smaller fingerlings and harvesting fish at smaller size compared to non-GIFT farmers whether the tilapia were grown in monoculture or polyculture. The fact that stocking smaller fish costs less and that the smaller size of fish harvested from that stocking are marketed at a lower price suggests this farming strategy is likely conditioned by lower financial resources of farmers and/or possibly targeting a different (lower cost) market segment. These data are consistent with GIFT farmers being relatively poor resource households.

Earlier publications of GIFT performance (Dey et al., 2000; Asian Development Bank, 2005; Acosta and Gupta, 2010) reported faster growth, better feed efficiency of the GIFT strain, and inferred the benefit of these attributes to greater yields and profitability to farming systems as a result. At the time of the introduction of GIFT, when there were few other if any improved strains in the farming systems, it would not be surprising to see marked differences between GIFT and other tilapia strains. Reports from on-station research (Khaw et al., 2008) and on-farm trial data (Haque et al., 2016) have continued to demonstrate faster growth and improved feed conversion ratio in GIFT. Given the existence of a number of improved strains, multiple introductions of tilapia into Bangladesh and the period of time elite strains have been available means the comparison of GIFT generation 12 in the present study with a range of non-GIFT stocks might not demonstrate as clear-cut differences. Nevertheless, our research results showed clearly that in the real farming environment in Bangladesh today, the GIFT strain generation 12 had a specific growth rate some 27–36% faster than non-GIFT tilapia in both monoculture and polyculture ponds. The lower survival rate for GIFT tilapia fingerlings relative to that observed in non-GIFT in polyculture ponds may reflect the smaller stocking size of GIFT fingerlings.

In previous studies (Dey et al., 2000; Asian Development Bank, 2005; Haque et al., 2016) a faster growth rate was seen as a key condition to obtain higher yields and associated with better feed conversion ratios. Our results demonstrated that the faster growth rate of GIFT resulted in difference in yield between GIFT and non-GIFT tilapia in monoculture systems. However, feed conversion ratios were not significantly different in GIFT and non-GIFT monoculture systems. Although a significant difference in FCR of GIFT and non-GIFT in polyculture systems was found (GIFT having the better value), we could not infer that GIFT was more efficient than non-GIFT as farming conditions and practices differ substantially among polyculture ponds.

Detailed analysis of gross profits, costs and benefit cost analysis showed higher economic performance of GIFT compared to non-GIFT ponds. Particularly in monoculture systems, faster growth rate is an important condition to result in higher yields for GIFT farmers, which then produced higher revenues and gross profits as well as benefit cost ratio.

Our study also highlighted that polyculture systems are the prevalent farming systems for tilapia in Bangladesh. Only a quarter of the farmers farmed tilapia in monoculture at the time of our survey. A difference in the practices between GIFT and non-GIFT farmers was observed in polyculture systems with respect to stocking of species other than tilapia with GIFT farmers stocking twice as much Pangasius catfish as non-GIFT farmers. In polyculture systems, GIFT farmers also had higher fish yield, revenues, gross profit and benefit-cost ratio than non-GIFT farmers.

Higher benefit to cost ratio can be interpreted to mean more cost-effectiveness (Kondylis et al., 2017) of GIFT relative to non-GIFT in both monoculture and polyculture systems. Cost-effectiveness is an important pre-condition for scaling of aquaculture innovations (Woltering et al., 2019; Sartas et al., 2020). Cost-effectiveness of GIFT compared to non-GIFT strains suggests GIFT is an “inclusive” aquaculture innovation, i.e. one that benefits smallholders as well as commercial scale aquaculture. Indeed, we found that the GIFT strain generates higher returns relative to cost of production for small scale farmers endowed with less assets compared with non-GIFT suggesting the potential for the GIFT strain to improve the livelihoods of resource-poor farmers.

Certain qualifications apply to interpreting our results. First, we depend on recall survey data, where farmers in developing countries often do not keep farm records. Second, the data used for analysis was one-time survey that does not capture time dynamics and fluctuation of aquaculture business cycle. Third, the study covers all regions of Bangladesh hence ensuring external validity of the results. We recognize that there may exist heterogeneity in the performance of GIFT across regions; the study could not analyze the performance by region due to the limited sample size. Our analysis compared GIFT against a group of all non-GIFT strains. However, a more disaggregated comparison of GIFT against specific non-GIFT strains might be more informative and generate better insights. Indeed, the discovery of the difference in approach by the GIFT and non-GIFT farmers underlines the need for more detailed work to understand the factors determining profitability and sustainability of these complex smallholder aquaculture systems. Furthermore, we recognize that the current study does not explain why small-scale farmers seem to prefer GIFT while larger-scale farmers have a preference for other strains. We hope future research could address these caveats including substantiating more clearly the impacts of the GIFT strains on the farmers’ welfare and explaining difference in preferences for strains.

5. Conclusions

Using recall survey data, this study confirmed that GIFT performed better than non-GIFT tilapia in terms of higher relative growth rate and more cost-effectiveness in both monoculture and polyculture in ponds in Bangladesh. Difference in yield was observed between GIFT and non-GIFT in both monoculture and polyculture ponds when considering tilapia yield only. The findings of this study have several important implications for policy and aquaculture development. Benchmarking information on performance is important to support investment and efforts in scaling GIFT. Specifically, the result implies that scaling the profitability of GIFT would be welfare enhancing to grow-out aquaculture producers. There exists an opportunity to further extend the productivity frontier by promoting adoption of improved management practices among farmers. Such practices may further reduce the feed conversion ratio associated with GIFT hence increasing profitability.

The findings further suggest important impacts of GIFT. They confirmed that high performance of GIFT in terms of average yield and profitability shown by on-station and on-farm trial studies is found in farming systems. This is a key condition in order to improve welfare and achieve associated economic, social and environmental benefits. Follow-up studies will be required to explore the impacts of GIFT adoption on these additional benefits.

Author statement

The authors declare that they have contributed to the research.

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.

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Appendix A. Appendix

Table A1
Balancing tests for GIFT farmers and matched non-GIFT farmers under monoculture.

	Mean			t-Test	
Variable	GIFT	Non-GIFT	Bias reduction (%)	t-Stat	p-value
Assets index (scores)	1.71	1.71	98.5	0.05	0.96
Age (years)	40.07	39.99	97.4	0.05	0.96
Education (1 = respondent’s education > class X)	0.70	0.64	−340.0	0.73	0.47
Activity (fish farming is the main source of livelihood)	0.39	0.42	91.9	−0.35	0.73
Experience in tilapia farming (years)	5.01	4.20	−6540.0	1.18	0.24
Household members involved in aquaculture	1.35	1.47	−60.0	−1.03	0.31
Access to information on fish farming (1 = yes; 0 = otherwise)	0.24	0.27	45.0	−0.39	0.70
Access to credit (1 = yes; 0 = otherwise)	*0.21*	*0.34*	−80.0	−1.90	0.06
Attitude towards risk (scores)	15.04	16.62	−103.4	−0.96	0.34
Stocking density (numbers per square meter)	4.58	5.78	9.1	−1.22	0.23
Survival rate (%)	0.75	0.68	−177.3	1.60	0.11
Weight at harvest (g)	257.67	276.26	86.0	−1.05	0.30

Note: Significant differences between GIFT and non- GIFT farmers at $p < 0.05$ are given in bold and $P < 0.10$ (but >0.05) are given in italics.

Table A2
Balancing tests for GIFT farmers and matched non-GIFT farmers under polyculture.

	Mean			t-Test	
Variable	GIFT	Non-GIFT	Bias reduction (%)	t-Stat	p-value
Assets index (scores)	**1.87**	**2.05**	48.6	−3.12	0.00
Age (years)	40.69	40.35	86.4	0.39	0.69
Education (1 = respondent’s education > class X)	0.54	0.59	61.2	−1.15	0.25
Activity (fish farming is the main source of livelihood)	0.46	0.45	98.6	0.11	0.91
Experience in tilapia farming (years)	6.12	5.49	−751.5	1.34	0.18
Household members involved in aquaculture	**1.46**	**1.34**	25.9	1.98	0.05
Access to information on fish farming (1 = yes; 0 = otherwise)	*0.14*	*0.09*	−16.8	1.86	0.06
Access to credit (1 = yes; 0 = otherwise)	0.18	0.15	83.6	0.92	0.36
Attitude towards risk (scores)	**15.59**	**13.45**	−28.9	2.67	0.01
Stocking density (numbers per square meter)	4.23	4.21	98.9	0.95	0.95
Survival rate (%)	*0.73*	*0.69*	64.1	1.72	0.09
Weight at harvest (g)	307.72	290.98	83.7	1.61	0.11

Note: Significant differences between GIFT and non-GIFT farmers at $p < 0.05$ are given in bold and $P < 0.10$ (but >0.05) are given in italics.

Table A3
Matching quality indicators before and after matching.

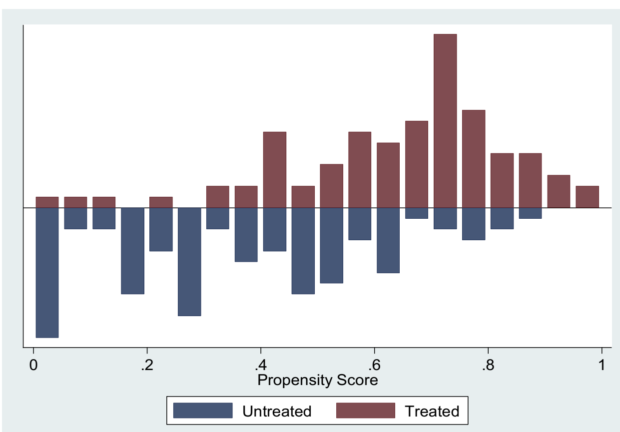
Matching algorithm	Pseudo R^2 before matching	Pseudo R^2 after matching	LR chi-square (*p*-value) before matching	LR chi-square (*p*-value) after matching	Mean standardized bias before matching	Mean standardized bias after matching
Monoculture	0.229	0.055	**52.08 (0.000)**	12.61 (0.398)	29.2	15.2
Polyculture	0.312	0.050	**204.16 (0.000)**	33.99 (0.001)	39.1	12.2

Notes: Matching based on nearest neighbour algorithm. Significant difference at 5% level are given in bold.

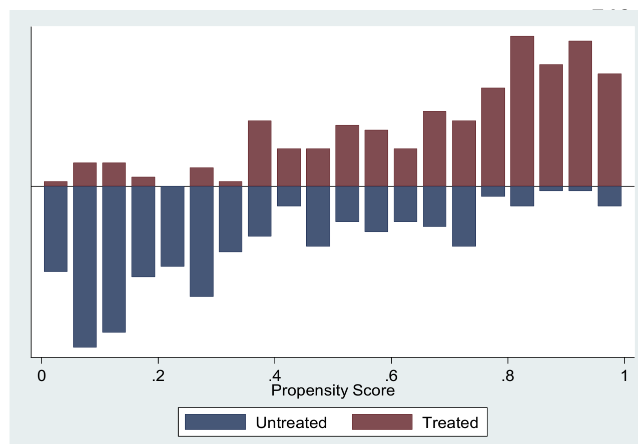
Table A4
Critical level of hidden bias (Γ) of GIFT and non-GIFT monoculture and polyculture systems.

	Critical level of hidden bias (Γ)	
Outcome variables	Monoculture	Polyculture
Specific growth rate (%/day)	1.6	2.4
Feed conversion ratio (FCR)	1.6	3.4
Average yield (metric tons/ha/per cycle)	1.3	1.1
Sale price ($US000/ton/cycle)	3.4	1.1
Revenue ($US000/ha/cycle)	1.1	1.1
Production costs ($US000/ha/cycle)	1.2	1.4
Gross profits ($US000/ha)	1.3	1.4
Benefit-Cost Ratio (BCR)	1.1	1.1

Note: The critical value of gamma (Γ), values below which the better performance of GIFT compared with non-GIFT would be questioned.



Panel 1. GIFT vs non-GIFT in monoculture



Panel 2. GIFT vs non-GIFT in polyculture

Fig. A1. The distribution of the estimated propensity scores by GIFT (treated) and non-GIFT (untreated) strains farmed under monoculture and polyculture systems. The individual bars indicate groups of treated (above the horizontal line) and untreated (below the horizontal line) couples that can be compared and demonstrate that most groups have representatives from treated and untreated groups allowing valid comparison.

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