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Economic performance characterization of intensive shrimp (*Penaeus monodon*) farming systems in Bangladesh

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Abstract

Intensive shrimp (*Penaeus monodon*) production system is relatively new in Bangladesh, and has not yet been adequately described or its viability assessed. The aims of this study were to characterize, assess the economic performance and identify challenges for intensive shrimp farming in Bangladesh. A survey was conducted using a structured questionnaire enumerated between October 2016 to June 2017 with 53 farmers in three districts of Khulna Province, southwest Bangladesh. The surveyed farms were categorized into small, medium and large scale based on the number of culture ponds. The average production, operational costs, gross and net income, net income, and cost-benefit ratios were higher in large farms, followed by medium and small farms. A Cobb–Douglas production function model was used to identify factors influencing shrimp yields, with feed management, health management, pond depth and aeration identified as significant factors. The benefit-cost ratio was higher than 1, indicative of a positive investment efficiency of intensive shrimp farming system for farmers. Major challenges were associated with quality of inputs, high investment, maintenance of biosecurity and disease outbreaks, water quality, limited number of input suppliers and lack of diagnostic services and technical information at farm level. Our findings suggest that there is an urgent need for human capacity development for shrimp farm owners, workers and technicians. It is also important to improve access to quality inputs, rapid and affordable diagnostics and other technical services.

KEYWORDS
Cobb–Douglas production function, intensive shrimp farming, Penaeus monodon, production costs, profitability

1 | INTRODUCTION

Bangladesh is one of the world's leading aquaculture producing countries with a production of 2.49 million tons in 2018–2019 (DoF, 2019). Having a sub-tropical climate and a considerable area of brackish water, available resources and favourable environmental conditions provide a unique opportunity for coastal aquaculture in Bangladesh (Ahmed & Diana, 2015). The coastal area is mainly dominated by black tiger shrimp (*Penaeus monodon*) farming. About 75% of shrimp farms are located in the southwest of Bangladesh and the annual production was estimated at 63,171 tons from 185,308 ha area in 2018–2019 (DoF, 2019). Bangladesh exported 33,363 tons of fish and fish products valued at US$ 383 million in 2018–2019, of which US$ 274 million (71%) was from shrimp exports (DoF, 2019). It contributes significantly to the national economy as the second largest export commodity after ready-made garments. The shrimp farming industry generates diverse employment opportunities, with more than 87,000 people directly involved in farming activities, and another 5000–6000 families involved in the value chain such as post larvae (PL) trading, shrimp harvesting, marketing, processing and exporting (BBS, 2017).

In Bangladesh, shrimp farming began in early 1970s and grew rapidly during the 1980s. The rapid growth was associated with (i) the successful development of hatcheries and post larvae production, (ii) geographical expansion of production area, (iii) high profit margins to farmers (Alam & Phillips, 2004; Islam et al., 2003) and (iv) the increased global demand for seafood (Ahmed & Diana, 2015). The rapidly increasing demand for shrimp by national and international markets has prompted farmers to intensify production. The initial attempts of intensification were started in Cox's Bazar in 1993 but collapsed due to an outbreak of white spot disease caused by White Spot Syndrome Virus (WSSV) in 1994 (Karim et al., 2012).

According to the level of inputs used, shrimp farming in Bangladesh can be broadly categorized into three types: (1) Extensive culture, where shrimp depend entirely on naturally occurring organisms in the ponds for their growth, (2) semi-intensive culture, which utilizes both natural productivity, application of fertilizer and occasionally supplementary feeding to enhance growth, and (3) intensive culture, in which shrimp obtain nutrients primarily from artificial feeds and are stocked at higher densities, necessitating management practices such as aeration and pond drainage to maintain water quality (Tenison-Collins, 2016).

Many factors have shaped the development of shrimp farming in Bangladesh including shrimp diseases, changes in water salinity, trade-related shocks, social conflicts and the rising prices of inputs, however farming has remained based largely on traditional practices with a low per unit area productivity (Belton et al., 2011). This is why shrimp farm productivity is low in Bangladesh compared to neighbouring shrimp-producing countries in Asia (Karim et al., 2012, 2014; Kumaran et al., 2017; Nguyen & Ford, 2010). Therefore, government and non-governmental organizations attempted to promote intensive shrimp farming to improve the productivity and sustainability of shrimp culture in Bangladesh (Shrimp Foundation, 2012).

Results of previous studies indicated that, there are significant opportunities to improve shrimp production in Bangladesh through intensification and the adoption of better management practices (Karim et al., 2014; Rahman et al., 2019). They also indicated that, increasing stocking density of shrimp, prawn and fish seed slightly increase returns. The intensive shrimp farming system in Bangladesh is relatively new and still developing with limited available information. The farming system appears to have good potential for further improvement of the shrimp industry in Bangladesh as it plays a vital role in export earnings. Therefore, shrimp production needs to be increased through the targeted application of inputs. Research described in this paper was conducted to assess the productivity of shrimp, production costs and profitability of intensive farming system. In addition to this, there was an aim to identify the challenges in order to support future efforts to promote the intensive farming system in Bangladesh.

2 | MATERIALS AND METHODS

2.1 | Study area and sampling frame

This study was conducted in the major shrimp producing districts of Bangladesh, namely Bagerhat, Khulna and Satkhira (DoF 2019). We have conducted key informant (KI) interviews with the Department of Fisheries (DoF) officials ($n = 10$) to develop a sampling frame for intensive farms. The DoF has a compiled list of the intensive shrimp farms for each district. Farms were selected based on some criteria (such as cultured in excavated pond, monoculture, batch stocking and harvesting, stocking density >5 PL/m^2, used commercial pelleted feed and aeration). KI interviews with farmers ($n = 12$) and feed and chemical suppliers ($n = 7$) were conducted to identify newly constructed farms and each farm was visited to collect basic information including farm and/or owner name, starting year, farm area, number of ponds, farm ownership and specific location. A total of 89 farms owned by 82 farmers were identified for the sampling frame.

2.2 | Data collection

A structured questionnaire was developed to collect information about (1) the socio-economics of farmers/managers, (2) farm infrastructure, (3) farming system (seed stocking, feed management, aeration, labour management, common diseases, biosecurity, water and waste management), and (4) farm yield for the 2016 calendar year. The questionnaire was piloted with farmers ($n = 4$), followed by necessary modifications and clarifications. The farm survey was conducted from October 2016 to June 2017. Farms were visited to obtain the consent of farm owners and/or managers to participate in the survey and to collect information on farm size and water salinity. In total, 53 out of 82 farmers (16 in Bagerhat, 28 in Khulna and nine in Satkhira) agreed to participate in the survey. The surveyed intensive farms were categorized into small ($n = 31$), medium ($n = 14$) and large ($n = 8$) based on the number of operating ponds. The number of ponds for small, medium and large-scale farms was ≤5, 6–15 and >15, respectively. Each farmer was interviewed once, even if he/she owned multiple farms or multiple sites. Further information on the intensive farming system were collected through KI interviews with the experienced farmers ($n = 5$), feed and chemical suppliers ($n = 4$) and DoF officers ($n = 6$).

2.3 | Data management and analysis

Data were coded and entered into a customized electronic MS Access database (Microsoft Corporation, Redmond, WA, USA) and

TABLE 1 The equations for calculating production costs and returns of intensive shrimp farming

Total cost	= Variable costs + Fixed costs
Variable costs	= cost of seed, feed, chemical, labour (family and hired), electricity, fuel, harvesting & marketing and miscellaneous
Fixed costs	= Cost of depreciation + land lease
Depreciation costs	= (Purchase price-salvage value)/economic life
Gross revenue	= Total production × actual sold value
Net margin	= Gross revenue – total cost
Benefit-cost ratio (BCR)	= Gross revenue/Total cost

then exported to MS Excel (Microsoft Corporation) and Statistical Package for Social Science, SPSS 16.0 (SPSS, Chicago, IL, USA) for analysis.

A probability of less than 5% ($p < 0.05$) was considered as significant in all instances, except where stated otherwise in the text. An economic analysis was conducted to determine net returns from intensive shrimp production system (Ali et al., 2016a; Ali, Rahman, Rico et al., 2018). The analysis was based on the actual prices of production inputs and the total sales of outputs, expressed in US dollars (USD 1 = BDT 81.20). Table 1 shows the equations used for calculating costs and returns.

2.4 | Production function model

The Cobb–Douglas (C–D) production function model was used to assess the production efficiency of intensive shrimp farming system. Several studies have applied this model to analyse fish culture systems (Ali et al., 2016a; Karim et al., 2017; Nisar et al., 2021). Ten explanatory variables (stocking density, feed, chemical, labour, pond size, pond age, pond depth, crop duration, aeration and owner's experience in intensive farming) were assumed to explain shrimp productivity by C–D production function model. It was hypothesized that all of these variables would affect shrimp productivity. Regression analysis (ordinary least squares method) was used to assess the effect of these variables. The C–D production function model used was expressed in the following general form:

$$\mathrm{Log}Y = \log a + \sum b_i \log(X_i) + \log U_i. \quad (1)$$

However, the empirical C–D production function models used for this study, one with seed types, training, nursery and location dummies (3) and the other without (2) are expressed as follows:

$$\begin{aligned}\mathrm{Log}Y_i = \log a &+ b_1\log X_{1i} + b_2\log X_{2i} + b_3\log X_{3i} + b_4\log X_{4i} \\ &+ b_5\log X_{5i} + b_6\log X_{6i} + b_7\log X_{7i} + b_8\log X_{8i} \\ &+ b_9\log X_{9i} + b_{10}\log X_{10i} + \log U_i\end{aligned}, \quad (2)$$

$$\begin{aligned}\mathrm{Log}Y_i = \log a &+ b_1\log X_{1i} + b_2\log X_{2i} + b_3\log X_{3i} + b_4\log X_{4i} + b_5\log X_{5i} \\ &+ b_6\log X_{6i} + b_7\log X_{7i} + b_8\log X_{8i} + b_9\log X_{9i} + b_{10}\log X_{10i} \\ &+ d_1D_1 + d_2D_2 + d_3D_3 + d_4D_4 + d_5D_5 + d_6D_6 + \log U_i\end{aligned}, \quad (3)$$

where, Y is shrimp yield (MT/ha), a is a constant, mathematically interpreted as the x-axis intercept, X_1 stocking density (post-larvae/m^2), X_2 feed input (MT/ha), X_3 chemical input (kg/ha), X_4 labour (man-day/ha), X_5 pond area (ha), X_6 pond age (years), X_7 pond depth (m), X_8 crop duration (days), X_9 aeration (hours), X_{10} operator experience of intensive farming (years), D_1 (1: Satkhira; 0: otherwise), D_2 (1: Khulna; 0: otherwise), D_3 (1: if farm operator received training; 0: otherwise), D_4 (1: stocked SPF PL; 0: otherwise), D_5 (1: stocked PCR tested PL; 0: otherwise), D_6 (1: used nursery pond; 0: otherwise), b_1–b_5 is the coefficient of the relevant variables, U_i the indexes of observations (1,2,3…n).

3 | RESULTS AND DISCUSSION

3.1 | Characteristics of farming communities

The study participants were farm owners (57%), farm managers (42%), and farm technicians (2%) (Table 2). The farm operators were middle aged, ranging from 20–55 years with an average of 38±8.7 years. The formal educational level of farmers did not differ significantly ($p > 0.05$) between farm location and scale. This was with the exception of one owner and three farm technicians had a bachelor's degree in aquaculture. This level of educational attainment is considerably higher than the national average (World Bank, 2010), and other aquaculture farming systems in Bangladesh (Ali et al., 2016b). Farmers have been practicing traditional shrimp and/or prawn farming for 14 ± 7.0 years with no significant difference between farm scales. Large scale farm owners had a higher ($p > 0.05$) experience in intensive farming than small and medium scale farm owners. However, the level of experience is one of the challenges for the long-term sustainability of intensive farming system. Saengnoree and Label (2003) reported that education and experience on certain technology have improved farmers' knowledge to maintain intensive production and made the system sustainable. A high proportion of farms (68%) employed permanent workers while 32% of farms were operated by household members. The number of permanent workers (full-time or salaried seasonal labours) per farm varied from 1 to 120 (Table 2). Most farms (77%) had temporarily employed workers for one or more days for different purposes such as pond repair and shrimp harvesting.

3.2 | Intensive farm temporal growth trends

The number of intensive shrimp farms started growing at different rates in different locations since 2002 (Figure 1). The majority (63%) of farms were constructed between 2014 and 2016. In 2016, 89 intensive

TABLE 2 Characteristics of studies participants

Characteristics	Farm scales Small ($n = 31$)	Medium ($n = 14$)	Large ($n = 8$)	Overall average ($n = 53$)
Respondent role in the farm				
Owner, (%)	81	21	25	57
Manager, (%)	19	79	63	41
Technician, (%)	0.00	0.00	13	1.9
Respondent age, year	37 ± 9.2	41 ± 8.6	37 ± 6.6	38 ± 8.7
Education, years	11 ± 1.9	11 ± 2.5	11 ± 1.6	11 ± 2.0
Aquaculture experience, year	12 ± 5.8	16 ± 9.0	15 ± 6.6	14 ± 7.0
Intensive farming experience, year	4.0 ± 3.2	3.4 ± 2.5	5.6 ± 5.2	4.1 ± 3.4
Attended intensive farming education program, (%)	48	36	25	42
Number of labors per farm per cycle				
Household	1.5 ± 0.65	1.3 ± 0.58	0.00 ± 0.00	1.4 ± 0.63
Permanent	2.7 ± 2.3^{a}	12 ± 4.8^{b}	49 ± 38^{c}	16 ± 25
Temporary	16 ± 12	41 ± 56	29 ± 31	24 ± 33

Note: Different subscripts within rows indicate significant differences ($p < 0.05$).

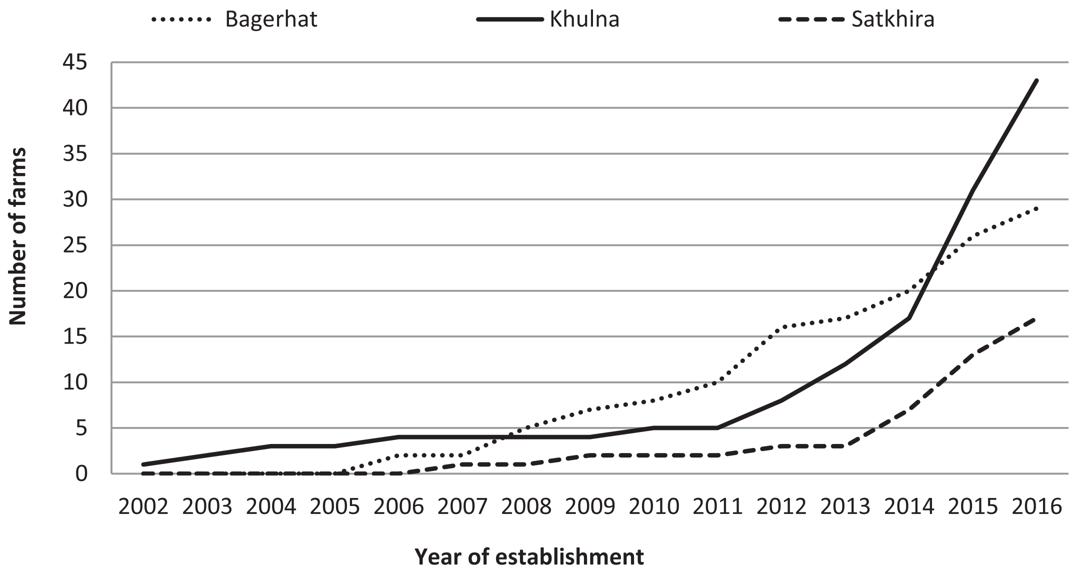

FIGURE 1 Temporal development of intensive shrimp farms in Bagerhat, Khulna and Satkhira in Bangladesh from 2002 to 2016

farms were in operation, covering 1100 ha, with an estimated total production of 4000 MT per year (5.4% of total shrimp production). The motivations to establish intensive shrimp farms were the presence of feed and chemical companies (94%) and the successful harvest of neighbouring farmers (47%). The results showed that intensive farms were developed by converting traditional shrimp and/or prawn ghers (74%), rice-field (19%) and fishponds (7.5%). This indicated that farmers are shifting to a more profitable production system (Karim et al., 2014).

3.3 | Farming practices

3.3.1 | Intensive shrimp farm characteristics

The majority of interviewed farmers (92%) were operating a single farm site, while 8% were operating multiple (2–3) sites. For farmers having more than one farming site, only one site was visited assuming that they are using similar management practices across the sites.

TABLE 3 Farm characteristics and management practices (average ±SD) by farm scales

Items	Farm scales Small ($n = 31$)	Medium ($n = 14$)	Large ($n = 8$)	Overall average ($n = 53$)
Farm characteristics				
Farm size (ha)	0.87 ± 0.86^a	8.6 ± 9.7^b	23 ± 18^c	6.2 ± 11
Farm water surface area (ha)	0.62 ± 0.58^a	4.1 ± 2.0^b	14 ± 7.5^c	3.6 ± 5.6
No of grow-out ponds farm^{-1}	1.7 ± 0.83^a	8.4 ± 2.8^b	29 ± 15^c	7.6 ± 11
Grow-out pond size (ha)	0.30 ± 0.14^a	0.43 ± 0.18^b	0.42 ± 0.09^b	0.35 ± 0.15
Pond depth (m)	1.4 ± 0.19^a	1.5 ± 0.19^{ab}	1.6 ± 0.11^b	1.47 ± 0.19
Farm with nursery ponds (%)	52	86	88	66
Nursery pond size (ha)	0.12 ± 0.11^a	0.27 ± 0.14^b	0.22 ± 0.06^{ab}	0.19 ± 0.13
Farm with reservoir ponds (%)	32	79	75	51
Reservoir pond size (ha)	0.20 ± 0.13^a	0.37 ± 0.15^b	0.33 ± 0.11^{ab}	0.30 ± 0.15
Source of PL				
Directly from hatchery, (%)	58	64	75	62
Through feed and chemical suppliers, (%)	35	36	25	34
Through local PL trader, (%)	6.5	0.00	0.00	3.8
Health checks for PL				
PCR tested for WSSV only, (%)	74	57	25	62
SPF (Specific pathogen free), (%)	23	43	75	36
Not tested, (%)	3.2	0.00	0.00	1.9
PL stocked nursery pond, (%)	48	57	75	55
Stocking density (n m^{-2})	9.5 ± 3.5	11 ± 3.0	11 ± 1.9	10 ± 3.2
Feeding (MT ha^{-1})	4.8 ± 2.6^a	6.5 ± 2.3^{ab}	7.7 ± 2.1^b	5.7 ± 2.7
Feed conversion ratio (FCR)	1.5 ± 0.26	1.5 ± 0.25	1.6 ± 0.19	1.53 ± 0.25
Average Production (MT ha^{-1})	3.1 ± 1.5^a	4.4 ± 1.4^b	4.9 ± 1.8^b	3.7 ± 1.7
Average size of harvested shrimp (g)	44 ± 6.6^a	47 ± 11^{ab}	54 ± 13^b	46 ± 9.5
Survival rate, (%)	75 ± 16	80 ± 15	81 ± 24	78 ± 17
Crop duration (days)	130 ± 22	131 ± 16	130 ± 14	130 ± 19
Water source				
River, (%)	29	79	87	51
Canal, (%)	71	21	13	49
Level of water salinity (g/l)	7.0 ± 3.0^a	10 ± 2.5^b	10 ± 3.5^b	8.3 ± 3.3
No. of filter to screen inlet water	3.2 ± 0.78	3.3 ± 0.73	3.0 ± 0.53	3.2 ± 0.73
Water exchange/top up (% of farms)	42	64	88	55
Water exchange/top up frequency (times/crop)	3.9 ± 1.7	4.1 ± 3.2	3.3 ± 3.0	3.8 ± 2.5
Water exchange/top up (% of total water in pond)	26 ± 13	22 ± 11	22 ± 7.0	24 ± 11

Note: Different subscripts within rows indicate significant differences ($p < 0.05$).

The farm size and the water surface area ranged from 0.09 to 60 ha and from 0.06 to 29 ha, respectively (Table 3). There were no significant differences in farm size and water surface area among farms in the three districts. The number of grow-out ponds per farm and the mean pond size varied from 1 to 60 and from 0.06 to 1.0 ha, respectively (Table 3). A pond size of 0.16–1.0 ha was considered optimal for efficient management of intensive cultivation of shrimp in Thailand and Taiwan (Kongkeo, 1997). The mean pond size was significantly lower ($p < 0.05$) in Khulna than Satkhira district. This could be due to the conversion of traditional fish ponds into intensive shrimp ponds in Khulna. Most farmers were able to construct uniform size ponds that might facilitate pond management and avoid difficulties associated with large surface areas. Similar pond sizes have previously been reported for intensive shrimp farming systems in Bangladesh (Ghosh et al., 2013; Karim et al., 2014). Our results also indicated that, most medium and large-scale farms included nursery and reservoir ponds (Table 3).

The pond depth ranged from 1.1 to 1.8 m (Table 3). Pond water depths were significantly shallower ($p < 0.05$) in small scale farms than large scale, with pond depths in medium farms at an intermediate level. The shallow pond depth in small farms was partly a result of the method of pond construction, which involved digging soil from the bottom of ponds to repair dikes at lower capital investment than the excavation of large volumes of soil from below ground level in medium and large farms. However, ponds in intensive shrimp farms were deeper than those in the traditional shrimp farming systems in Bangladesh (Ali et al., 2016b; Jahan et al., 2015). Globally, the most common average depth for shrimp ponds ranges from 0.3 to 2.0 m and there is a positive correlation between the pond depth and intensification (Krummenauer et al., 2016). Our study indicated that ponds were well constructed with higher dikes for maintaining biosecurity and to protect from flooding.

3.3.2 | Farm operations

Water supply and pond preparation

The source of water for 51% and 49% of farms was directly from the river and canals, respectively (Table 3). Water was pumped into farms either by shallow pumps or electric motors. Most of the large (88%) and medium (79%) farms used primarily river water, whereas most of the small farms (71%) were using canals as primary water source. All farms were using nets at water inlets to remove any objects from the water. By the end of the production cycle, ponds were drained using pumps and left to dry for 30–90 days or until the pond bottom soil cracked. After drying, 62% of farmers used liming compounds at the rate of 123–247 kg ha^{-1} to treat the pond surface area. After filling with water, all farmers treated pond water with bleaching powder at a rate of 40–65 ppm and left for 5–10 days. Then, treated pond water was conditioned before stocking with minerals, probiotics, yeasts and molasses in 57%, 81%, 9.4% and 17% of farms, respectively.

Seed stocking

A high proportion of farmers (62%) purchased PL directly from hatcheries and other farmers reported purchasing PL from feed suppliers, chemical suppliers or local PL traders (Table 3). A higher proportion of large scale farms (75%) purchased directly from a hatchery compared to medium (64%) and small (58%) scale farms. Out of 53 farms, 62% purchased WSSV free PL (PCR tested), 36% purchased SPF PL and 1.9% purchased non-tested PL (Table 3). Almost all intensive shrimp farms in Thailand and Sri lanka purchased and stocked PCR tested PL (Mahagamage & Jayakody, 2020; Thanh, 2014). A higher percentage of small-scale farms purchased WSSV free PL compared to the medium and large-scale farms, and the opposite trend was observed for SPF PL. This may be due to the limited availability, higher price of SPF PL and purchasing power of large-scale farm owners compared to medium and small-scale farms.

Most of the farmers (55%) stocked PL into nursery ponds and the remainder stocked PL directly to grow-out ponds (Table 3). The rearing periods in nursery ponds were 25–40 days and subsequently transferred to grow-out ponds. It was found that nursed juveniles had a higher survival rate, growth and better uniformity in size than non-nursed juveniles (Islam & Alam, 2008; Yta et al., 2004). All farms in this study, followed a single batch stocking and harvesting strategy (i.e., all in–all out) of a monoculture system. The stocking densities of PLs or juveniles varied from 4.2 to 17 m^{-2} (Table 3) depending on the seed size. The stocking density in the present study was lowered compared to other Asian countries (Kumaran et al., 2017; Thanh, 2014; Zhang, 2014). The mean stocking density at grow-out ponds did not differ significantly between districts and farm scales, but a significant difference ($p = 0.001$) was observed between farmers who stocked PL directly to grow-out and those who nursed them to juveniles beforehand.

Feeds and feed management

All farmers used commercially manufactured pellet feed for shrimp with a crude protein content of 35%–40%. The feeding rates ranged from 2.2% to 12% of the biomass, with higher rates at the beginning of the production cycle. Feeding frequency was four times per day at 06:00, 11:00, 17:00 and 22:00 hours and the total feed per day was distributed in different proportions of 30%, 20%, 30% and 20%, respectively, according to instruction of the feed companies. In 75% and 25% of farms, feed was distributed manually using boats and from the dikes, respectively. Zhang (2014) reported that shrimp farms in China distributed feed using hand/manually by staff from dike, boat or feeding site. Feeding from dikes was observed in small farms contrary to medium and large farms. Feeding rate was adjusted on a daily basis according to the observations of feed trays, 2 h after each feeding.

The total amount of feed per production cycle varied from 1.6 to 11 MT ha^{-1} (Table 3) and the quantity of feed used per hectare was found to be significantly higher ($p < 0.05$) in largescale farms compared to small ones. This might indicate better market access and financial capacity of large-scale farms. The feed conversion ratio (FCR) ranged from 1.0 to 2.4 and did not differ significantly ($p > 0.05$) between farm locations and scale. This is in accordance with Hasan et al. (2012) and Kumaran et al. (2017), who found similar FCRs for shrimp culture in India. This wide range FCR could be attributed to many factors as feed quality, farm management, availability of natural feed and others.

Water quality and waste management

All farmers reported using chemical and biological products as a preventive measure, to treat pond water and/or sediment, or as nutritional supplements to improve digestibility and the health of shrimp. The complexity of application of health products in the context of quality assurance, efficacy, value chain (manufacturing, marketing), requirement on the basis of scientific evidence suggest further studies with comprehensive overview and regulatory reform (IMAQulate project unpublished results).[1] The frequency of monitoring water quality parameters (pH, ammonia, dissolved oxygen, alkalinity and

[1] https://www.stir.ac.uk/about/faculties/natural-sciences/aquaculture/research/aquaculture-research-projects/imaqulate/

salinity) varied from daily to twice per month and the tendency was found to be higher in large scale farms compared to small ones.

It was noticed that all farmers used paddlewheel aeration for the entire culture period, primarily to improve the level of dissolved oxygen. It also helped to promote the accumulation of wastes in the pond centre, thus making it easier to remove. Increasing the minimum dissolved oxygen showed better results including high survival rates, yields and net income (McGraw et al., 2001; Ruiz-Velazco et al., 2010). The number of aerators (2 HP) per pond and number of paddles per aerator varied from 1 to 6 and 2 to 10, respectively, based on the pond size, stocking density and the biomass. Farmers fixed the position of the aerators in the corners of the pond prior to stocking. The aerators were operated four times per day, with a total of 3–16 hrs per day (the lowest was at the first month of stocking and the highest was at the last month of the production cycle). There was no significant variation in aeration practices between districts and farm scale.

More than half of farms (55%) exchanged or topped up pond water with irregular intervals (1–10 times per crop) and this tendency was found to be higher in large scale farms compared to medium and small ones (Table 3). Only the topped-up water method was used in intensive shrimp farms to exchange water (Thanh, 2014). The total rate of exchange or topping up varied from 5% to 50% over the culture period and was not differed significantly ($p > 0.05$) between farm locations and scale. This result is consistent with previous studies and modelling calculations for shrimp aquaculture in Asian countries (Rico & Van den Brink, 2014). All farmers discharged wastewater, including pond sediment, to the surrounding environment at the end of the production cycle. Twenty-one percent of farmers discharged wastewater during the culture period at irregular intervals, via a central concrete tube. In addition, few farms (5.7%) removed pond sediments manually at the end of the production cycle and used them for repairing pond dikes. All farms discharged wastewater without any treatment, with most farms discharging directly into canals (64%), rivers (21%), fallow land (9.6%) and into other farms (5.7%). This untreated wastewater may contain high nutrient loads, pathogens or potentially toxic chemical residues that may subsequently contribute to the deterioration of the surrounding aquatic ecosystems (Rico & Van den Brink, 2014; Sun et al., 2016).

Farm biosecurity

Generally, most visited farms followed few biosecurity measures to prevent diseases. Biosecurity in terms of preventing vectors, sources of contamination and internal cross contamination are effective methods for protection (Horowitz & Horowitz, 2003; Lightner, 2003). All farmers set nets around the farms to exclude potential vectors for disease such as crabs, frogs and other animals. Moreover, 63% of large, 14% of medium and 9.7% of small-scale farms used nets around each individual ponds to prevent transmission of pathogens between ponds. In addition, 7.5% of large and medium scale farms used bird nets over the ponds. All large, 93% of medium, and 48% of small farms assigned workers to specific ponds, to minimize the risk of transmission of pathogens between ponds. Potassium permanganate and iodine were used for footbaths, equipment disinfection and for washing hands before and after handling shrimp. Sixty-eight percent of small, 64% of medium, and 50% of large farms used chlorine (bleaching powder) at varying frequency (1–6 times per cycle) to disinfect footpaths and dikes.

Production

The average production of intensive shrimp farms was 3.7 ± 1.7 MT/ha/crop (Table 3). The production was lower compared to shrimp production in other Asian countries (Kumaran et al., 2017; Thanh, 2014; Zhang, 2014). However, significantly ($p < 0.05$) higher yields were found in large (4.9 ± 1.8 MT/ha/crop) and medium (4.4 ± 1.4 MT/ha/crop) scale farms compared to small ones (3.1 ± 1.5 MT/ha/crop). The difference in the yields between farm scales may be due to the application of higher rates of feed, better access to technological support or following of better management practices. The results (Figure 2) showed that 75% of farms produced between 1.5 to 5.5 MT/ha/crop while 5.5% of farms produced < 1.5 MT/ha/crop. The low production level may be attributed to shrimp mortalities at the early stage of the culture cycle, low stocking densities and/or short crop duration. On the other hand, 17% of farms achieved yields >5.5 MT/ha/crop. These farms were well-financed operations, used higher quantities of feed, had greater investment in farm management (such as higher stocking densities, use of SPF PL) and had a longer culture period. The finding from the present study is consistent with Paul and Vogl (2011) and Hossain et al. (2013), who reported a yield of 2–6 MT/ha/crop.

There was a positive linear correlation between the yield, stocking density, pond depth, water salinity and crop duration (Figure 3). These results were in agreement with previous studies which found a correlation between yield and stocking density (Karim et al., 2014), pond depth (Johnson et al., 2000), salinity (Kumar et al., 2012) and crop duration (Kumaran et al., 2017; Ruiz-Velazco et al., 2010) for intensive shrimp farming. The yield of shrimp was negatively correlated with pond age (in years) and this is consistent with earlier studies (Jackson & Wang, 1998) on shrimp farming in Australia

Data were analyzed to explore the relationship between yield and other parameters such as seed size at the time of stocking (PL versus juvenile), source of water (river versus canals) and seed categories (SPF, PCR tested and non-tested). There was no significant difference in the yield of farms stocked PLs or juveniles. This may be due to the starting stocking density where farms stocked PLs have a higher density than those stocked juveniles. The yield of shrimp farms using water directly from the river (4.3 ± 1.8 MT/ha/crop) was significantly higher ($p = 0.01$) than those using water from canals (3.1 ± 1.4 MT/ha/crop). This could be due to the significantly higher ($p = 0.03$) water salinity in river (9.3 ± 3.5 g/l) compared to canal (7.3 ± 2.9 g/l). High yields were found to be associated with high salinities (Kumar et al., 2012). The yield was significantly higher ($p = 0.01$) in farms stocked SPF compared to non-SPF PLs. Wyban (2015) reported that SPF seeds were associated with high growth and survival rate, contributing to a higher yield compared to non-SPF seeds.

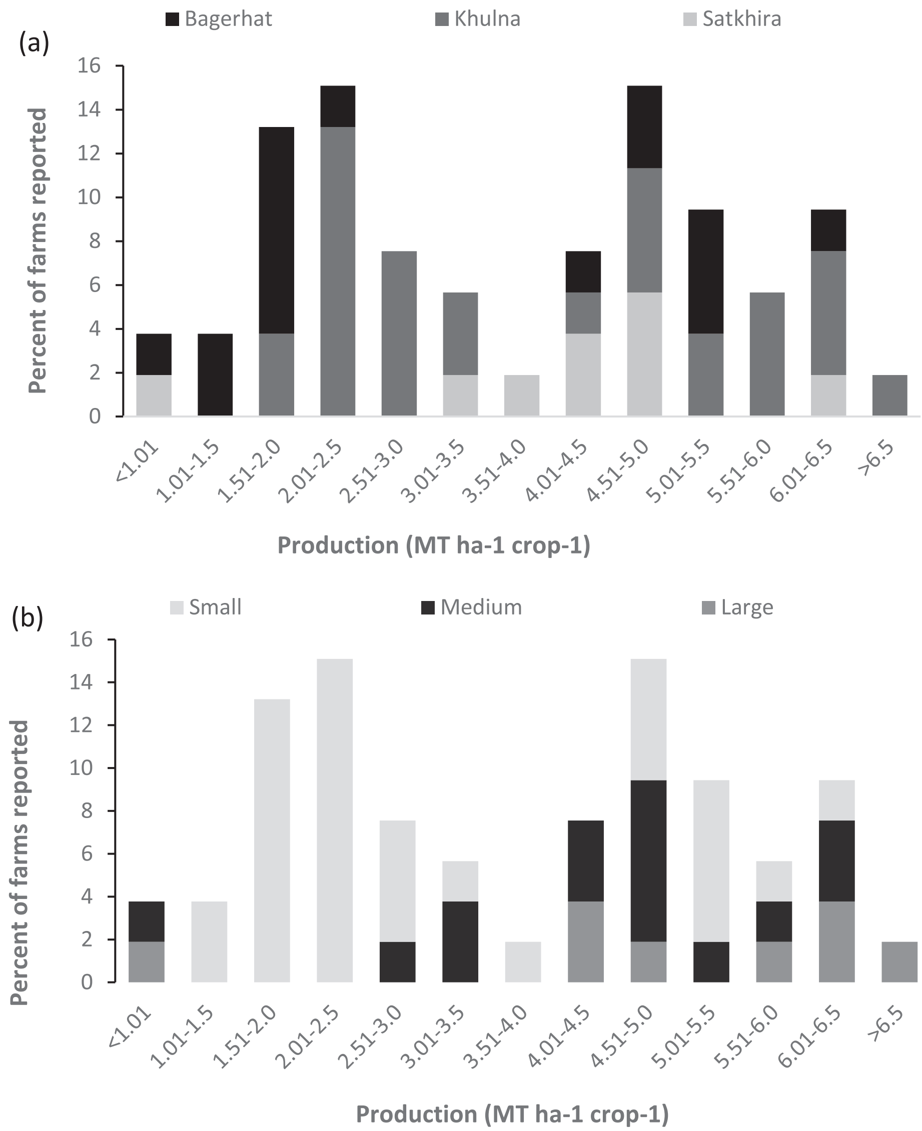

FIGURE 2 Frequency distribution of production in MT ha^{-1} $crop^{-1}$ of shrimp by (a) farm location and (b) farm scales

Disease occurrence and health management practices

Almost all farms had no equipment for disease diagnosis except one farm had a microscope. In most farms (87%), chemical and feed supplier technicians were the decision makers for health management whereas 13% of farmers had their own technician/s to make decisions. On farm health management and monitoring included observing feed trays (94%), weekly shrimp sampling (74%) and testing samples to identify pathogens (3.8%). More than 50% of farms did not report a major disease outbreak over the last year. The most commonly observed diseases and/or clinical signs are listed in Table 4. A greenish scum on the shrimp body was reported by 21% of farms and occurred between May and July 2016. Black gill was reported by 15% of farms, with black spots under the carapace on the shrimp. This is mainly caused by the accumulation of nitrogenous wastes in the pond bottom with high levels of ammonia and nitrite, usually at the end of the grow-out period (MacRae et al., 2002). Thirteen percent of farms reported the occurrence of white spot disease (WSD) and had emergency harvest. About 11% of farmers reported clinical signs such as reduction in feed consumption and changes in the hepatopancreas (light and shrunken) within 20–60 days of PLs stocking and resulted in about 100% mortalities. These clinical signs are similar to acute hepatopancreatic necrosis disease (AHPND) infection. These observations have been also reported by Schryver et al. (2014) and Li et al. (2016) for intensive shrimp farming in China. However, further investigations are required to identify/confirm the causative agent of these problems for intensive shrimp farming in Bangladesh. Recent publications suggested AHPND infection in shrimp farms in Bangladesh (Ahmmed et al., 2019).

Harvesting and marketing

The average weight of shrimp at harvest ranged from 28 to 80 g per piece, after 90 to 180 days grow-out period (Table 3). Most farmers (75%) used seine nets and 25% used cast nets to harvest shrimp after draining of 10%–100% and 70%–100% of water, respectively. It may

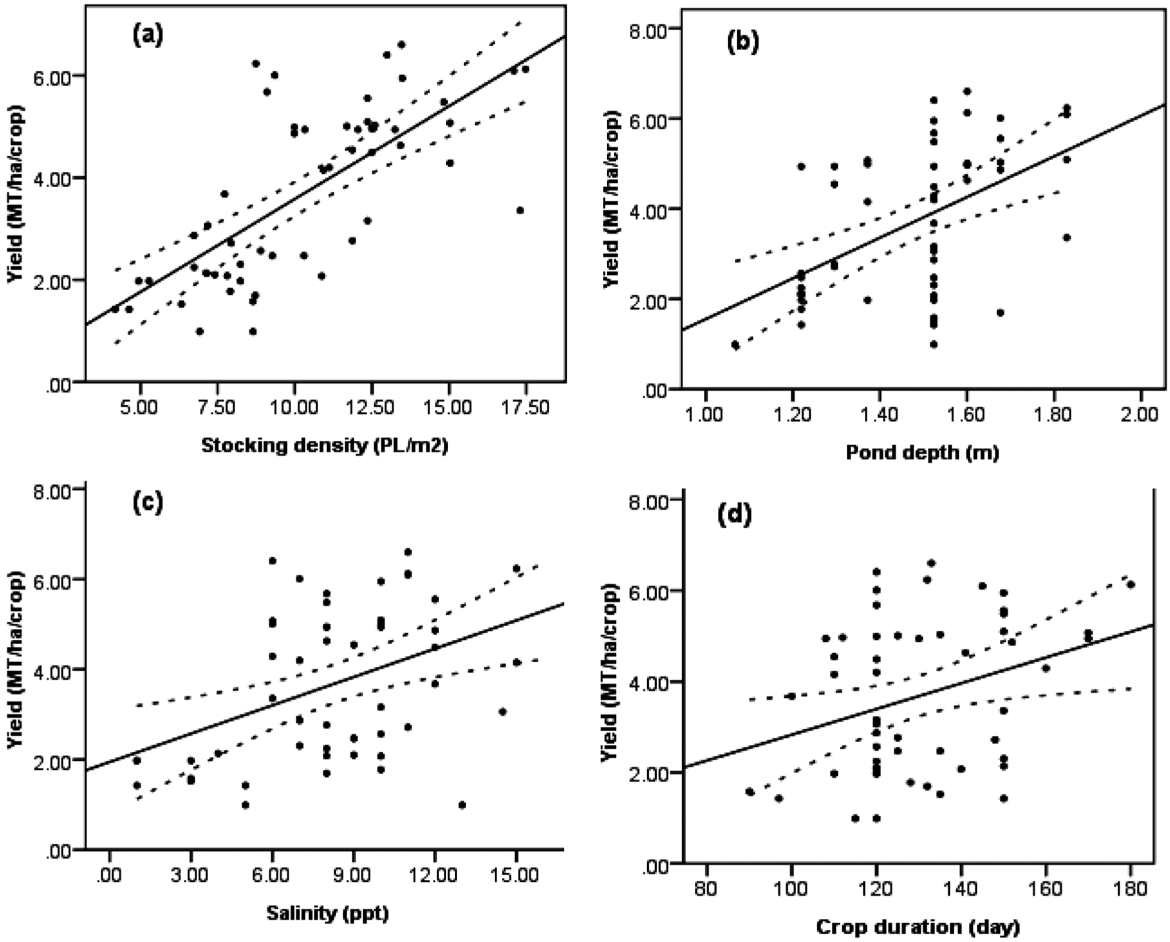

FIGURE 3 Relationship between yield (MT/ha/crop) and (a) stocking density (PL m^{-2}), (b) pond depth (m), (c) water salinity (ppt), and crop duration (days). Broken lines represent 95% confidence limits for mean predicted values

TABLE 4 Diseases and clinical signs reported by the intensive shrimp farmers in Bangladesh

Disease/ syndrome	% of farms	Major clinical sign observed
White spot disease	13	White spot mainly on carapace and/or sometimes a little bit on whole body surface, sluggish movement, less appetite
Black gill	15	Black spot on gill under carapace, bacterial erosion on carapace and gill
Greenish scum	21	Greenish scum on shrimp body
Vibriosis	1.9	Reddish discolour, dark brown colour on body
Antenna broken	1.9	Antenna broken
Soft shell	5.7	Shell is thin and persistently soft, shell is rough and wrinkled, lethargic, slow growth rate
Unknown disease	11	cessation of feeding, light and shrunken hepatopancreas

take up to three days to complete the harvesting process. The middlemen buyers usually provide transport from the farm gate to the processing factories for the harvested shrimp. But if farmers decided to sell directly to the processing factories, they have to provide transport. Forty-seven percent of farmers sold shrimp directly to the processing factories through a commission agent. On the other hand, 53% of the farmers sold shrimp to commission agent/middlemen at the farm gate (after negotiating price and checking shrimp size) who brought shrimp to the depots for further sale. Thanh (2014) reported that 55% of intensive shrimp farms in Thailand sold their harvested shrimp directly to processors and farmers from remote areas mainly sold to collectors who came directly to the pond site. Most of the large (88%) and medium (71%) scale farms sold shrimp directly to processors whereas small scale farms (58%) sold shrimp to commission agents. The buyer usually

TABLE 5 Average production costs and returns for intensive shrimp farming system by farm scales

Cost and returns (USD ha^{-1})	Farm scales (mean ± SE) Small	Medium	Large	Average (mean ± SE)
Variable cost (VC)				
Feed	7036 ± 681[a]	9208 ± 826[ab]	11,152 ± 1200[b]	8231 ± 526
Seed	1270 ± 79	1422 ± 95	1400 ± 74	1330 ± 54
Labor	2035 ± 190	2359 ± 117	2005 ± 302	2116 ± 124
Chemical	3179 ± 298	4605 ± 777	5077 ± 1179	3842 ± 332
Electricity and fuel	2610 ± 302[a]	4283 ± 690[b]	4102 ± 743[b]	3277 ± 292
Harvesting and marketing	289 ± 30	307 ± 52	302 ± 50	296 ± 23
Miscellaneous	355 ± 45	467 ± 97	412 ± 145	393 ± 42
Sub-total	16,775 ± 1266[a]	22,651 ± 1378[b]	24,451 ± 3142[b]	19,486 ± 1035
Fixed cost (FC)				
Depreciation	1606 ± 152	1764 ± 148	2477 ± 624	1779 ± 137
Land leased	924 ± 43	921 ± 21	931 ± 7.5	924 ± 26
Sub-total	2530 ± 154	2684 ± 144	3408 ± 622	2703 ± 138
Total cost (TC) = VC+FC	19,305 ± 1356[a]	25,335 ± 1488[b]	27,859 ± 3109[b]	22,189 ± 1096
Gross income (GI)	32,439 ± 3308[a]	46,532 ± 5013[ab]	55,970 ± 8889[b]	39,713 ± 2925
Net income (NI = GI-TC)	13,134 ± 2208[a]	21,196 ± 4077[ab]	28,111 ± 6503[b]	17,524 ± 2053
Benefit-cost ratio	1.63 ± 0.08	1.79 ± 0.15	1.94 ± 0.21	1.72 ± 0.07

Note: Different subscripts within rows indicate significant differences ($p < 0.05$).

checked samples for body weight prior to purchasing. However, some farmers sold shrimp from the farm gate by tender according to different weight categories. It was observed that the market chain for intensive shrimp farming is relatively shorter than that for traditional farming (Ahmed et al., 2008). However, the current shrimp market value chain is not suitable for implementation of traceability. This study suggests that short market chains (producers to processors) should implement a traceability system which is particularly important for exporting shrimp (Shrimp Foundation, 2018). Most farmers (83%) had a prior contract with commission agents and 70% of farmers received instant cash payment from the buyers. Sometimes farmers (23%) received late payment from the buyers, ranging from 50%–100% of the total estimated price. However, 7.5% of farmers received prior payment from the buyer, ranging from 4%–50% of the total estimated price.

3.4 | Production costs and profitability

The annual production costs of intensive shrimp farming system ranged from USD 7846 – 36,347 ha^{-1} (Table 5). The mean annual cost per hectare was significantly higher ($p < 0.05$) in large and medium farms than small farms. This was due to higher variable costs including feed, seed, chemicals, electricity & fuel, harvesting and marketing. The annual variable costs were higher ($p < 0.05$) in large and medium farms compared to small farms (Table 5). Variable costs accounted for about 88% of total costs across the three farm scales. This is in line with Karim et al. (2014) and Nisar et al. (2021), who found similar feed cost structures in intensive shrimp production: 91% and 90%, respectively. A significantly higher ($p < 0.05$) feed cost was found in large farms (USD 11,152 ± 1,200 ha^{-1}) than small farms (USD 7036 ± 681 ha^{-1}), with feed costs in medium farms (USD 9208 ± 826 ha^{-1}) at an intermediate level. Feed was the major cost involved in the intensive shrimp culture that solely accounted for around 42% of the total variable costs. This is consistent with Karim et al. (2014) for intensive shrimp production in Bangladesh. However, a higher level of feed costs was reported by Nisar et al. (2021), accounting for 80% of total variable costs for more intensive shrimp production in India.

The estimated annual costs for chemicals in small, medium and large farms were USD 3179 ± 298 ha^{-1}, USD 4605 ± 777 ha^{-1} and USD 5077 ± 1179 ha^{-1} respectively, with no significant difference ($p > 0.05$) between farm scales. The mean annual costs per hectare for electricity and fuel were significantly higher ($p < 0.05$) in medium and large farms compared to small farms. Electricity and fuels are important inputs in the intensive shrimp production for aeration of ponds. Nisar et al. (2021) observed similar findings in intensive shrimp production in India. Lastly, farmers in all three scales reported similar seed, labour, harvesting and marketing and miscellaneous costs (Table 5). The mean annual fixed cost was USD 2703 ± 138 ha^{-1} (Table 5) and it accounted for 12% of total costs across all farm scales. A similar result was also reported by Karim et al. (2014), who found that fixed costs accounted for 9% of total costs for intensive shrimp production in Bangladesh.

The annual gross income was significantly higher ($p < 0.05$) in large farms compared to small farms (Table 5). The net income was higher ($p < 0.05$) in large farms (USD 28,111 ± 6503 ha^{-1}) compared to

TABLE 6 Estimated values of coefficients and related statistics of the C-Ds production function

Explanatory variables	Model 1	Model 2
Y-intercept	0.01 (1.05)	−1.30 (1.42)
Stocking (X_1)	0.01 (0.04)	0.01 (0.05)
Feeding (X_2)	0.58 (0.05)[c]	0.55 (0.06)[c]
Chemical (X_3)	0.21 (0.10)[b]	0.19 (0.12)[b]
Labor (X_4)	0.00 (0.01)	0.00 (0.02)
Pond size (X_5)	0.01 (0.70)	−0.25 (0.82)
Pond age (X_6)	−0.06 (0.05)[a]	−0.08 (0.07)[a]
Pond depth (X_7)	0.55 (0.58)[b]	0.50 (0.69)[b]
Crop duration (X_8)	0.01 (0.00)	0.00 (0.01)
Aeration (X_9)	0.11 (0.06)[a]	0.10 (0.07)[a]
Intensive farm experience (X_{10})	0.04 (0.03)	0.04 (0.04)
D1		0.21 (0.15)[a]
D2		0.10 (0.17)
D3		0.12 (0.11)
D4		0.25 (0.27)[a]
D5		0.10 (0.40)
D6		0.14 (0.16)
R^2	0.90	0.92
Adjusted R^2	0.86	0.88
F-value	48.87[c]	27.38[c]
Return to scale $\sum b_i$	1.45	1.99

Figures within parentheses indicate standard error.
[a]Significant at $p < 0.1$.
[b]Significant at $p < 0.05$.
[c]Significant at $p < 0.01$.

small farms (USD 13,134 ± 2208 ha^{-1}), while medium (USD 21,196 ± 4077 ha^{-1}) farms were at intermediate level. The benefit-cost ratio (BCR) was the highest ($p > 0.05$) in the large farms, followed by medium and then small farms. This is consistent with previous studies (Jahan et al., 2015; Karim et al., 2014; Nisar et al., 2021), suggesting intensive shrimp farming system in Bangladesh has been a sustainable and profitable industry for many years. This also suggests that shrimp production could be consider as a business with potential.

3.5 | Production function model

The estimated values of the coefficients and related statistics of the C–D production function model are presented in Table 6. Regression analysis showed that the coefficient of multiple determinations (R^2) for Model 1 was 0.90, implying that 90% of the variation in shrimp production can be explained by the ten explanatory variables (stocking density, feeding, chemical, labour, pond size, pond age, pond depth, crop duration, aeration and owner intensive farm experience) included in the model. Six dummy variables for seed types, training, nursery and location (model 2) increased R^2 to 0.92. Both models were highly significant (ANOVA; $p < 0.00$). These findings are similar to those of Karim et al. (2014) and Ali, Rahman, Jahan et al. (2018). Results of model 1 indicated that shrimp production was significantly influenced by feeding ($p < 0.01$), chemical ($p < 0.05$), pond depth ($p < 0.05$) and aeration ($p < 0.10$). The estimated coefficients for feeding, chemical, pond depth and aeration were 0.58, 0.21, 0.55 and 0.11 respectively, meaning that (keeping other factors constant) a 10% increase in feeding, chemical, pond depth and aeration, would increase shrimp production by 5.8%, 2.1%, 5.5%, or 1.1% respectively. This suggests that more attention should be paid to these parameters when trying to increase shrimp production. Ali et al. (2016a) and Nisar et al. (2021) found that feeding, chemical and pond depth positively influenced fish and shrimp production. Conversely, the model also shows that pond age affected shrimp production negatively and was statistically significant at the 10% level of significance. The estimated coefficient of pond age indicated (holding other variables constant) that with a 10% reduction in pond age, shrimp production will increase by 0.06%. For model 2, the estimated coefficients for feeding, chemical, pond depth and aeration were 0.55, 0.19, 0.50, and 0.10 respectively.

The dummy variables were included in the model to assess the sensitivity (if any) of shrimp production to qualitative factors (Kurbis, 2000). The dummy variable for Satkhira (D_1) was significant ($p < 0.10$) when compared to Bagerhat district, however Khulna (D_2) district was not significantly different from Bagerhat district. Despite this, there was a positive relationship between shrimp production and the dummies for all locations. The dummy variable for farm owner received training (D_3) was not statistically significant, implying that there were no significant differences in shrimp production between farmers who received training or not. The dummy variable for stocked SPF seed (D_4) was found to have a statistically significant ($p < 0.10$) effect on shrimp production; however, there was no significant effect for stocked PCR tested seed (D_5). This indicates that SPF seed resulted in better shrimp production than non-SPF seed which is consistent with Wyban (2015) for intensive shrimp production.

3.6 | Challenges

The major challenges for intensive shrimp farming were: disease outbreaks, quality of inputs (seed, feed, chemicals), high investment, maintenance of biosecurity, water quality, limited number of input supplier and lack of diagnostic services and technical information at farm level. Diseases were the greatest threats to successful intensive shrimp production given the lack of biosecurity and rapid affordable diagnosis. The lack of training was found to be a major limiting factor for diagnosis and health management, particularly for emerging diseases (Ali, Rahman, Rico et al., 2018). There is a need for effective aquatic health services to design and implement preventative and mitigation strategies for aquatic diseases. The lack of high-quality inputs is another constraint caused by limited supplies and suppliers for seeds, feeds, chemical and biological products. Increased awareness and stricter regulatory measures are required to improve the quality of production inputs and for efficiency of distribution channels of the inputs.

4 | CONCLUSIONS

The production costs, gross incomes, net incomes and BCR were higher in large than medium and small-scale farms. The BCR was >1 for all farms that indicated intensive shrimp production system is a profitable business. The feeding, chemical, aeration and pond depth were important factors for increasing shrimp production suggesting more attention should be paid to these parameters for increasing shrimp production. The main production challenges identified were: diseases, quality of production inputs, limited suppliers which cause price hike and lack of technical information. Regulatory reforms are required to improve the quality and efficiency of distribution channels of inputs particularly seed and feed. Feed technicians and chemical suppliers are the main source of information and dictating the farm management which leads to vulnerability and misinformation and potential market failure. Therefore, further studies are required to assess the efficacy and cost-benefit of health products currently used under field conditions in Bangladesh. Access to diagnostic and aquatic health services should be improved through education and training, and provision of more responsive public services. Therefore, an innovative approach is needed, including the role of government and private sector, to improve the culture practices and make them more sustainable.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

ETHICS STATEMENT

This study was a part of a wider project for which ethical approval got from the Animal Welfare and Ethical Review Body (AWERB) at the University of Sterling.

HUMAN ETHICAL STATEMENT

All data collection tools were approved by the University of Sterling. Study participants were assured of anonymity and confidentiality.

AUTHOR CONTRIBUTION

Hazrat Ali: Conceptualization; Data curation; Formal analysis; Methodology; Writing – original draft. Muhammad Meezanur Rahman: Writing – review & editing. Ahmed Jaman: Data curation; Formal analysis; Investigation; Validation. Siddhwartha Kumar Basak: Data curation; Formal analysis; Investigation; Validation. Mahmoud Eltholth: Formal analysis; Writing – review & editing. Francis Murray: Funding acquisition; Project administration; Resources; Writing – review & editing

DATA AVAILABILITY STATEMENT

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

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1002/aff2.29

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SUPPORTING INFORMATION

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