Aquaculture 596 (2025) 741730

Contents lists available at ScienceDirect

Aquaculture

journal homepage: www.elsevier.com/locate/aquaculture

Transformation of the farm segment of the aquaculture value chain in southern Bangladesh

Hazrat Ali [a,b,*], Mohammad Mahfujul Haque [b], Khondker Murshed-e-Jahan [a]

[a] WorldFish, Bangladesh and South Asia Office, Dhaka, Bangladesh
[b] Department of Aquaculture, Bangladesh Agricultural University, Mymensingh, Bangladesh

ARTICLE INFO

Keywords:
Structure
Conduct
Performance
Farm segment
Bangladesh

ABSTRACT

Aquaculture in Bangladesh has experienced rapid growth over the last three decades, yet technological changes in the farming segment remains underexplored. To address this gap, we surveyed 721 farmers across seven districts in southern Bangladesh from November 2020 to February 2021. The result showed moderate growth in aquaculture, with an 11 % increase in farmers and a 15 % rise in waterbodies over the past decade. Farmers cultivated diverse aquatic species, with carp dominating production at 56 % followed by crustaceans (16 %) and tilapia (14 %). Shrimp are more highly susceptible to disease than fish and prawn but, only 19 % of farmers adopted measures to enhance survival. The study noted a shift from shrimp to prawn and from crustaceans to fish due to disease, market demand, and environmental factors, resulting in intensification and greater use of floating feed over the last decade. A mere 0.55 % of farmers reported losses, spoilage, or wastage during harvest or between harvest and sale of aquatic products, with the volume being minimal at just 0.52 %. Aquaculture production segment generated 401,536 full-time equivalent (FTE) on-jobs in the seven surveyed districts, predominantly for family labor. This segment also demonstrates strong profitability, with an average benefit-cost ratio (BCR) of 1.98, indicating nearly a twofold return on investment. This study highlights the evolving dynamics of aquaculture in southern Bangladesh, revealing modest growth, increased species diversification, and shifts in production practices, which underscore the sector's profitability and need for improved technological adoption on a global scale.

1. Introduction

Aquaculture has emerged as a dynamic and rapidly growing sector within the global food system, accounting for nearly half (49 %) of the world's fish consumption (Troell et al., 2014; Bush et al., 2019; FAO, 2022). Global aquaculture production reached a significant milestone of 122.6 million tons in 2020, with inland aquaculture contributing 44 % and coastal and marine aquaculture making up the remaining 56 % (FAO, 2022). The prevailing global trend in aquaculture, including in Bangladesh, is marked by the intensification of production, driven by the increased use of feed and seed (e.g., El-Sayed et al., 2015; Belton et al., 2018; Hernandez et al., 2018; Naylor et al., 2021; Boyd and McNevin, 2022). Bangladesh has experienced significant expansion, diversification, and technological advancement in its aquaculture sector over the past two decades, transitioning toward more intensive cultivation methods (Belton and Azad, 2012; Bunting et al., 2017; Hernandez et al., 2018; Dey and Surathkal, 2020). The country's aquaculture output surged from 124,000 tons in 1984 to 2.73 million tons in 2022 (DoF, 2022), largely driven by the widespread adoption of hatchery-produced fish seed and manufactured fish feeds (Mahmud and Nazrul, 2013; Hasan and Arthur, 2015; Bosu et al., 2016; Shikuku et al., 2021). This expansion has resulted in a substantial increase in productivity, rising from 2580 kg/ha in 2002 to 5129 kg/ha in 2022 (DoF, 2022). The vast majority (94 %) of this aquaculture production is consumed domestically (Hernandez et al., 2018), contributing to a significant rise in fish consumption (Dey and Surathkal, 2020), with daily per capita intake increased from 49.50 g in 2010 to 67.8 g in 2022 (HIES, 2023). Additionally, the rapid expansion of aquaculture production has helped stabilize fish prices in the domestic market (Deb et al., 2022a), although challenges related to market power concentration among retailers remain (Deb et al., 2022b).

The aquaculture and fisheries sectors are essential to Bangladesh, providing food, income, and export revenues. They contribute about 22 % to agricultural GDP, 2.08 % to national GDP, and 1.05 % to export

* Corresponding author at: WorldFish Bangladesh Office, House # 335/A, Road #114, Gulshan, Dhaka 1212, Bangladesh.
E-mail address: h.ali@cgiar.org (H. Ali).

https://doi.org/10.1016/j.aquaculture.2024.741730
Received 29 January 2024; Received in revised form 1 September 2024; Accepted 4 October 2024
Available online 9 October 2024

earnings. Bangladesh earned USD 480 million in 2021–2022 from exporting nearly 74,043 tons of fish and fisheries products (DoF, 2022). These sectors supply about 60 % of the nation's animal protein and offer significant employment opportunities for rural small-scale farmers and laborers, though the exact scale of employment remains underexplored (Belton et al., 2014; Jahan et al., 2015; Gilson et al., 2023).

The rapid evolution of aquaculture in Bangladesh has led to a scarcity of up-to-date information on the characteristics and organization of its production segment. Research in this area has been grouped into three main themes (Hernandez et al., 2018). The first theme, farm diffusion and efficiency, examines the adoption of new technologies in aquaculture and their effectiveness in enhancing production (Ahmed et al., 2010; Alam et al., 2012; Karim et al., 2014; Sarker et al., 2016; Meah and Akther, 2021). The second theme focuses on the environmental interactions of aquaculture farms and the environmental impacts of these practices (Deb, 1998; Sohel and Ullah, 2012; Hossain et al., 2013; Islam and Yasmin, 2017). The third theme, livelihoods, explores the socio-economic impact of aquaculture, including its role in supporting local communities, generating income, and ensuring food security (Deb, 1998; Toufique and Gregory, 2008; Swapan and Gavin, 2011; Bondad-Reantaso and Subasinghe, 2013; Paprocki and Cons, 2014). The present research landscape within the aquaculture production segment has highlighted a gap in assessing technological changes over time, both in Bangladesh and globally (Hernandez et al., 2018). Moreover, a substantial portion of the existing studies relies on limited or non-representative surveys, or case studies focused on specific communities (Hernandez et al., 2018), with few large-scale statistically representative surveys of aquaculture technology to date.

The southern region of Bangladesh is a key aquaculture hub, known for its combination of export-oriented black tiger shrimp (*Penaeus monodon*) and freshwater prawn (*Macrobrachium rosenbergii*) production alongside domestic fish production. This region features diverse aquaculture systems, including improved extensive methods for shrimp, as well as semi-intensive and some intensive approaches (Karim et al., 2014; DoF, 2022; Ali et al., 2022). These systems operate in both freshwater and brackish water environments and are often integrated with rice or vegetable cultivation (Ahmed and Garnett, 2010; Wahab et al., 2012; Bunting et al., 2017; Ignowski et al., 2023). Freshwater aquaculture focuses on polyculture in ponds, while coastal systems involve shrimp and fish polyculture in "ghers" ponds (Apu, 2014). Despite rapid technological advancements, perceptions of the sector often lagging far behind the current reality, (Karim et al., 2014; Karim et al., 2016; Hernandez et al., 2018), presenting challenges in formulating and managing development strategies, as well as in making appropriate investments, policies, and interventions.

To address the existing gaps in the literature, this study aims to evaluate the structure, technological advancements, and performance of the farming segment within the aquaculture value chain in southern Bangladesh. Drawing from Porter's (1985) conceptualization, we view value chains as an industrial organization framework that facilitates the procurement of production inputs, their conversion into outputs, and the subsequent distribution and utilization of these outputs in various production or consumption sites. For the aquaculture production segment under study, we analyzed the number, size, geographical distribution, and asset ownership of farms (structure), alongside species composition and procurement and marketing practices (conduct). Additionally, we examined how changes in these factors influence key performance indicators, including loss and waste, employment, financing terms, profit margins, and vulnerability to disease risks.

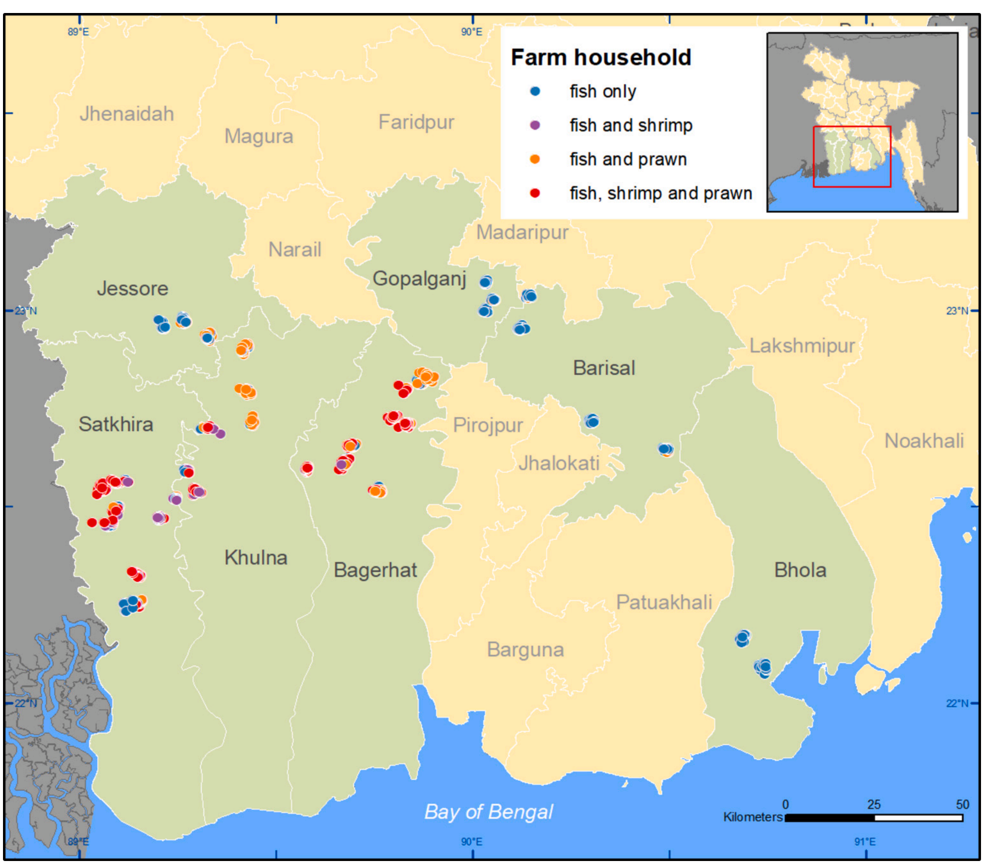

Fig. 1. Map of location of surveyed aquaculture farm in Southern Bangladesh.

2. Materials and methods

2.1. Study area

This research was carried out across the seven main aquaculture districts in southern Bangladesh, as illustrated in Fig. 1. The districts were selected purposively for inclusion in the survey due to their significant aquaculture production. These districts collectively represented 43 % of the national aquaculture area and contributed to 24 % of the national aquaculture production in 2022, and 88 % of the aquaculture area and 80 % of the production in southern Bangladesh (DoF, 2022). Aquatic species cultured in this area comprised a mix of fish such as Indian major carps, Chinese carps, tilapia, indigenous brackish water fish species, shrimp (primarily black tiger shrimp), and giant freshwater prawn. In subsequent analysis we classify farms into four distinct types, determined by the combination of species cultivated by farmers. These categories are outlined as follows: (1) Fish only (FO), characterized by the cultivation of various fish species within a polyculture system. (2) Prawn and fish (PF), wherein prawn was cultivated alongside different types of fish species within a polyculture system. (3) Shrimp and fish (SF), featuring the cultivation of shrimp alongside different types of fish species in a polyculture system. (4) Prawn, shrimp, and fish (PSF), representing farms where both prawn and shrimp were cultivated alongside various fish species within a polyculture system.

2.2. Survey methods and data

Data were gathered between November 2020 and February 2021 through an extensive survey covering 721 aquaculture farms (284 FO, 165 PF, 61 SF and 211 PSF farms). This survey is based on the second round of a previous study conducted in 2013. The selection of districts in the 2013 survey was purposeful, focusing on their significance in aquaculture production. The initial sample frame encompassed all *upazilas* (sub-districts) with notable aquaculture production, chosen randomly through proportional probability to size (PPS), resulting in the inclusion of 13 upazilas in the final sample. Within each selected upazila, a subsequent stage of trimming eliminated *mouzas* (administrative sub-units) with fewer than 20 aquaculture farms, based on the 2008 national agricultural census. Subsequently, two to three *mouzas* were randomly chosen from each upazila for inclusion in the farm survey.

In every selected *mouza*, 20 aquaculture farms were randomly chosen for interview from a pre-survey farm census. In 2020, to replicate the sampling approach, a new listing of aquaculture farmers was conducted in each *mouza* surveyed in 2013. Farmers still operating their farms in 2020 and who had participated in the 2013 survey, were resurveyed (80 % of the original sample). For respondents from the 2013 survey whose farms had closed or who were unavailable for the resurvey, replacements were randomly selected from the 2020 census list of aquaculture farmers following similar demographic and farming characteristics of 2013 survey farms.

The 2020 surveys were based on the structured questionnaires developed in 2013 but were adjusted to accommodate the current context and incorporate any additional questions identified during scoping activities. The questionnaires were translated into Bengali and piloted before finalization. In addition to the individual surveys, structured focus group discussions (FGDs) were held in each surveyed *mouza*. Key informants, including experienced farmers, local union council members, and religious leaders, participated in the FGDs. A total of 36 FGDs were conducted in all 36 *mouzas* included in the survey to gather 'meso-scale' data about facilities, transport access, and aquaculture-related businesses, and observed changes over time. This comprehensive approach provided a broader understanding of the factors influencing aquaculture production, including the availability and accessibility of infrastructure and services within the community.

2.3. Data analysis

The data was retrieved from the KoBo Collect platform in Excel format and then imported into Stata 17.0 (StataCorp LLC, College Station, Texas 77,845 USA) for statistical analysis. A one-way analysis of variance (ANOVA) was conducted, followed by a Duncan Multiple Range Test (DMRT) to assess the significance of variations among the average variables in different farming categories. A probability of less than or equal to 5 % ($p \leq 0.05$) was considered significant in all instances, unless otherwise specific in the text. The descriptive findings were supplemented with qualitative insights obtained from focus group discussions.

3. Results and discussion

3.1. Farmer demographic characteristics

The study highlights traditional gender roles in aquaculture, with 98 % of household heads being male, surpassing the national mean of 87 % (BBS, 2022). This reflects deep-rooted gender dynamics in Bangladesh and add a gendered dimension to aquaculture practices. The mean age of household heads was 49 years, with a mean of 6.4 years of education (Table 1). This educational level aligns closely with the national mean of 6 years in Bangladesh (World Economics, 2022), suggesting a consistent educational background across various farm categories. Aquaculture plays a central role in these households, with 58 % of members actively participating and 69 % identifying it as their primary occupation (Table 1). This trend is particularly strong in PF, SF, and PSF farms, where aquaculture serves as the main income source. Despite this focus, income diversification remains common among all farmers, consistent with broader trends in Bangladesh (Hernandez et al., 2018).

All surveyed farmers were landowners, with a mean landholding of 0.63 ha, which is notably larger than the regional mean (BBS, 2019). This larger land size underscores the importance of land as a critical asset, contributing to the sustainability and resilience of their aquaculture practices.

3.2. Structure

3.2.1. Farming communities

The meso-scale survey revealed that most households in the surveyed villages are engaged in crop farming (73 %) and aquaculture (56 %). Aquaculture participation increased by 11 % over the past decade, indicating a shift from horizontal expansion to intensification. Most

Table 1
Demographic characteristics of surveyed aquaculture farmers.

Variables	Farm category				
	FO	PF	SF	PSF	Overall
Mean age of household (HH) head (year)	51	47	50	49	49
Schooling year of HH head (year)	6.6	6.3	6.8	6.0	6.4
Gender of HH head (%)					
Male	96	99	98	99	98
Female	4	1	2	1	2
HH member participated in aquaculture (%)	59	55	56	61	58
Primary occupations of HH head (%)					
Fish farming	48	81	80	85	69
Trading	11	6	2	7	8
Others	13	4	2	2	7
Crop farming	12	3	1	0	5
Salaried job	6	5	5	4	5
Wage labor	8	1	10	2	5
Poultry/Livestock farming	2	0	0	0	1
% of HH had own land (%)	100	100	100	100	100
Own land area of HH (ha)	0.56	0.54	0.85	0.72	0.63

farmers (76 %) began aquaculture between 2000 and 2015 (Fig. 2), highlighting its relatively recent adoption and growing importance in the region. These trends align with previous studies showing rapid aquaculture development in Bangladesh since the 1990s (Hernandez et al., 2018). Furthermore, the survey noted a 15 % increase in the number of aquaculture waterbodies, suggesting new constructions or subdivisions of existing ones to meet the needs of a growing number of fish farmers. This ongoing infrastructure expansion reflects a sustained investment in aquaculture, underscoring its significance and the commitment to its continued growth in the region.

3.2.2. Land used by surveyed farmers

The surveyed farms had an average landholding of 1.12 ha (Table 2), which is three times greater than the national average for southern Bangladesh (BBS, 2019), highlighting their extensive land resources. Farmers allocated 70 % of their land to aquaculture, with proportions ranging from 43 % to 91 % across different farm types, reflecting the commercial nature of aquaculture in the area, as commercial fish farmers allocate a larger share of their land to aquaculture (Jahan et al., 2015). SF farms exhibited a significantly larger ($p \leq 0.05$) average aquaculture area compared to other farm categories. This shift is part of a broader trend, with land devoted to aquaculture increasing by 55 % over the past decade, signaling a growing emphasis on aquaculture production in the region.

Eighty-three percent of aquaculture waterbodies were inherited from family, while the remainder were either purchased or allocated by the government. About 68 % of these waterbodies were owned by farmers, with 25 % being rented, indicating a higher rental rate compared to crop farming in Bangladesh (Ahmed, 2013). Furthermore, around 74 % of waterbodies had been converted before use by the surveyed farmers, with 21 % previously serving as cropland. This supports the belief that many aquaculture sites were established on former rice fields (Belton, 2016), suggesting that farmers are transforming cropland into aquaculture waterbodies, likely due to the sector's profitability.

Farmers utilized various water sources for their aquaculture operations, with rainfed sources being the most prevalent, used by 76 % to 99 % of farms across different categories. Additionally, tidal flows supported 42 % of waterbodies, especially those used for crustacean farming. Waterbodies were 0.34 km from paved roads and 0.62 km from farmers' households, with FO farms located closer to households. This close proximity is characteristic of homestead aquaculture, which benefits from its nearness to farmers' households (Haque et al., 2015).

Table 2
The land characteristics and use practices by farmers.

Variables	Farm category				
	FO	PF	SF	PSF	Overall
Mean operated land area (ha)	0.82	1.10	2.00	1.27	1.12
Mean number of aquaculture waterbody	1.8	2.0	2.0	2.2	2.0
Mean aquaculture land area (ha)	0.35	0.78	1.82	1.05	0.78
Aquaculture land share of total land (%)	43	71	91	83	70
Mean sample waterbody area (ha)	0.29	0.59	1.37	1.00	0.66
Water area as % surface area of sample waterbody	79	78	86	83	80
Jointly operated waterbody (%)	16	6.8	4.1	6.2	9.6
Tenure status of waterbody (%)					
Owned	81	61	67	59	68
Rented	16	34	27	30	25
Owned and rented	3	5	6	11	7
Waterbody used at the time of acquisition (%)					
Aquaculture	71	69	83	80	74
Paddy field	23	26	14	16	21
Uncultivated	4	4	1	4	4
Others	2	1	2	0	1
Waterbody obtained by source (%), conditional on owning					
Inherited from family	86	80	96	77	83
Purchased	14	20	1	17	15
Khas land	0	0	3	6	2
Waterbody used for nursing seed (%)	6.2	4.1	5.8	6.0	5.6
Sources of water (%)					
Rainfed	98	99	76	88	93
Canal	7.0	23	31	47	26
Shallow tube-well	18	22	22	18	19
River	7.0	9.5	32	26	16
Deep tube-well	2	1	3	4	3
% of waterbody received pumped water	34	28	46	41	36
Mean distance of waterbody to road (km)	0.24	0.50	0.33	0.34	0.34
Mean distance of waterbody to household (km)	0.28	0.79	0.84	0.81	0.62

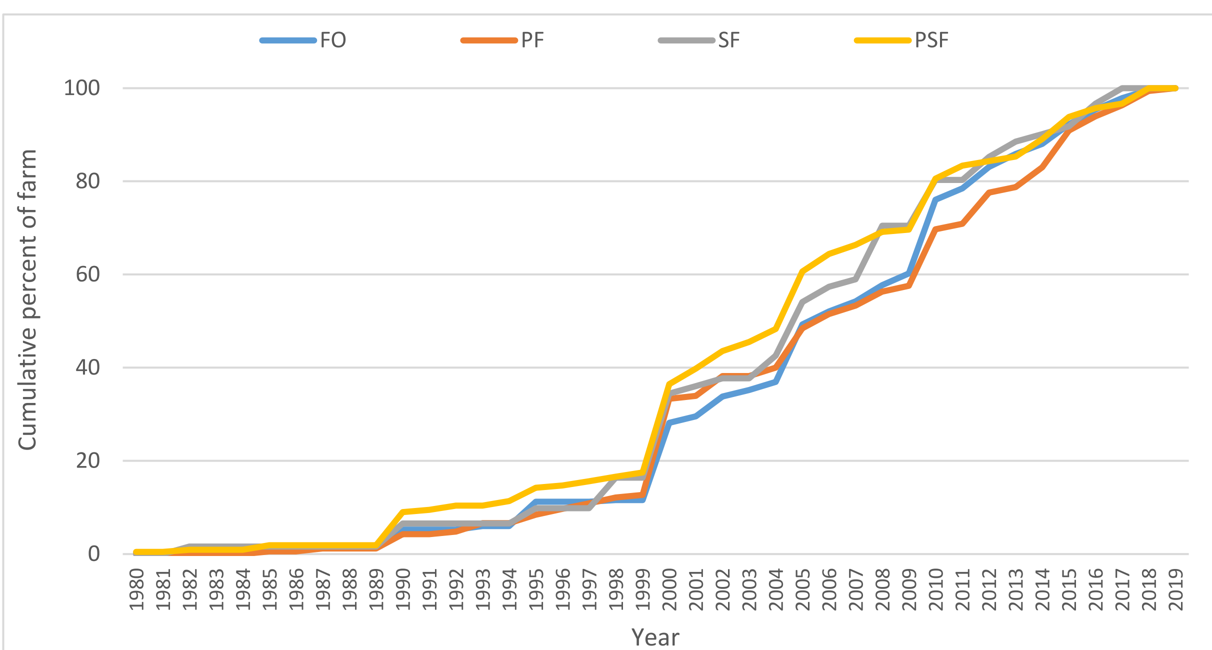

Fig. 2. A cumulative share of surveyed farmers began aquaculture by year.

3.2.3. Equipment and vehicle use

Farmers employed both self-owned and rented equipment for their aquaculture operations (Table 3). The mean value of personally owned equipment was USD 197, with PSF and SF farms making significantly larger investments ($p \leq 0.05$) compared to PF and FO farms, indicating a greater commitment to enhancing production. Ownership of water pumps increased from 14 % in 2013 to 33 % in 2020, with 51 % of farmers regularly renting them. Rented equipment values ranged from USD 5.2 for FO farms to USD 9.1 for SF farms.

Vehicle ownership was mainly bicycles (37 %), followed by motorbikes (11 %), human-haul vans (3.3 %), and autorickshaws (1.5 %). Only 0.5 % of PSF farmers owned trucks for transporting farm inputs and outputs. The mean value of owned vehicles was USD 446. Farmers relied heavily on rental vehicles, with human-haul vans (60 %) being the most rented, followed by autorickshaws (20 %), motorbikes (8.2 %), and engine vans (7.2 %). This indicates a significant dependence on third-party logistics services (3PLS), highlighting their essential role in farm input and output distribution and suggesting that transportation is a crucial yet underappreciated component of the fish value chain (Belton et al., 2018; Hernandez et al., 2018).

Table 3
List of equipment and vehicle used by aquaculture farmers.

Variables	Farm category				
	FO	PF	SF	PSF	Overall
% of farmers owning equipment					
Harvesting net	69	58	57	75	68
Aluminum pot	61	79	52	61	64
Plastic drum	42	62	67	77	59
Fishing trap	5.3	6.1	89	75	33
Water pump (hand tube-well)	20	33	26	30	26
Water pump (diesel)	14	31	28	37	26
Bamboo basket	15	15	34	26	20
Weighing scales	11	10	15	22	14
Boat	6.7	18	0	2.4	7.5
Water pump (electric)	5.6	10	13	4.7	7.1
Aerator	0.7	0	0	0	0.3
Mean value of owned equipment (USD)	151	186	248	249	197
% of farmers used rented or borrowed equipment					
Water pump (diesel)	56	53	41	46	51
Harvesting net	24	25	38	17	23
Plastic drum	19	19	11	11	16
Aluminum pot	16	6.7	18	14	13
Weighing scales	14	3.6	15	9	10
Bamboo basket	2.5	3.0	4.9	6.2	3.9
Water pump (hand tube-well)	5.6	1.2	1.6	4.7	4.0
Boat	2.1	0.6	3.3	5.2	2.8
Water pump (electric)	2.1	2.4	0	0.9	1.7
Generator				0.9	0.3
Mean value of rental equipment (USD)	5.2	7.3	9.1	8.5	7.1
% of farmers owning vehicle					
Bicycle	31	29	61	46	37
Motorbike	5.6	11	26	15	11
Human hauled van	2.5	4.2	4.9	2.8	3.2
Autorickshaw	2.5	0.6	0	1.4	1.5
Engine van	0.4	0.6	0	0	0.3
Truck	0	0	0	0.5	0.1
Mean value of owned vehicle (USD)	358	492	579	453	446
% of farmers used rented or borrowed vehicle					
Human hauled van	53	58	57	72	60
Autorickshaw	29	10	30	13	20
Motorbike	4.6	7.9	6.6	14	8.2
Engine van	3.9	4.8	11	12	7.2
Truck	1.1	0.0	4.9	2.8	1.7
Half-ton pick-up	0.7	0.6	0	3.8	1.5
Bicycle	1.4	0.6	3.3	1.9	1.5
Mean value of rental vehicle (USD)	7.0	11	7.9	12	9.9

3.3. Conduct

Aquaculture production cycles typically last about 314 days, with PF farms having a shorter cycle of 284 days and FO farms a longer cycle of 327 days. Farmers generally practice multiple stocking and harvesting throughout the year. Most (70 %) began their first stocking between February and June, while 86 % completed their final harvest between December and April, aligning with seasonal patterns.

3.3.1. Composition of aquatic food products

Farmers employed a polyculture system, cultivating an average of 8.9 aquatic species and harvesting a total of 32 distinct species across the sample. The primary focus was on carp, followed by tilapia and crustaceans, with other species produced in smaller quantities. The average production reached 3284 kg/ha, significantly higher ($p \leq 0.05$) on FO farms compared to others (Table 4). Carp accounted for 56 % of the total production volume and 36 % of the production value, consistent with national statistics from the Department of Fisheries (DoF, 2022). The proportion of carp production varied from 74 % in PF farms to 33 % in SF farms, with a notable increase in the southern region from 43 % in 2013 to 56 % in 2020, primarily due to reduced crustacean production. Rohu (*Labeo rohita*) was the predominant carp species, contributing 19 % of the total production and ranking third in national production (DoF, 2022).

Tilapia, produced by 72 % of farmers, accounted for 14 % of the total production but only 6 % of its value, reflecting its lower unit price compared to other fish species. Tilapia has risen to the second most produced fish in Bangladesh since the early 2000s (DoF, 2022), aligning with consumption trends (Hernandez et al., 2018). Tiger shrimp and freshwater prawn were the main crustaceans, together making up 14 % of production volume and 42 % of production value, highlighting their higher unit value. However, the share of crustaceans in total production volumes has decreased from 28 % in 2013 to 16 % in 2020. The survey indicates a shift in production practices from shrimp to prawn and a move toward domestically oriented fish, driven by market dynamics, disease issues, and environmental conditions. This transition reflects the broader trend of species diversification noted by Karim et al. (2012), Little et al. (2018) and Kim et al. (2022), which aims to manage disease risks and create alternative income sources.

FO farms also produced catfish, primarily pangasius, which contributed 13 % of both the total production volume and value (Table 4). Additionally, various freshwater and brackish species categorized as “other fish” contributed between 5 % and 14 % to the total production volume, with SF and PSF farms showing greater species diversity, potentially due to river water influx into shrimp farms.

3.3.2. Farmer procurement behavior

3.3.2.1. Seed. Surveyed farmers stocked a range of fish and crustacean seeds, with all farms stocking carp seeds and 72 % also including tilapia (Table 5). Additionally, 30 % of FO farmers and 10 % of PF farmers used catfish seed. Fish farms exhibited a significantly higher ($p \leq 0.05$) average annual stocking density of fish seeds (761 kg/ha) compared to crustacean farms (290 to 429 kg/ha), reflecting variations in farming practices driven by economic factors and species demand (Kumar et al., 2018; Engle et al., 2017). Crustacean farms stocked freshwater prawn and/or tiger shrimp post larvae (PL) with shrimp farms maintaining higher densities (196,197–223,336 PL/ha) compared to prawn farms (19,163 PL/ha), underscoring a marked preference for shrimp in crustacean aquaculture (Boock et al., 2016; Jamal et al., 2023). However, only 19 % of farmers nurtured PL prior to stock for grow-out farms, with minimal use of PCR (15 %) or SPF-tested PL (1.5 %). Farmers cited high costs, perceived ineffectiveness, and unavailability as reasons for not using PCR or SPF-tested PL. The low adoption rates of PCR and SPF tested shrimp PL, despite promotion by NGOs and the government for

Table 4
Types of aquatic foods species produced and shared by species.

Variables	Farm category									
	FO		PF		SF		PSF		Overall	
Mean species produced (no.)	8.1		9.7		7.8		9.8		8.9	
Mean aquatic food production (kg/ha)	4766[a]		2714[b]		1947[b]		2122[b]		3284	
Value of aquatic food products (USD/ha)	6874		5856		4862		6241		6285	
Species composition	% of volume	% of value	% of volume	% of value	% of volume	% of value	% of volume	% of value	% of volume	% of value
Tilapia	19	15	6	3	18	4	13	3	14	6
Indian major carp (IMC)										
Rohu	18	20	21	15	13	6	21	11	19	13
Catla	8	11	11	8	4	2	6	4	8	6
Mrigel	8	7	8	4	4	2	5	3	6	4
Other IMC	3	3	1	1	0	0	0	0	1	1
Sub-total	**36**	**41**	**41**	**29**	**22**	**11**	**32**	**17**	**34**	**24**
Exotic carp										
Silver carp	9	7	8	4	1	0	1	0	5	2
Grass carp	5	5	12	8	2	1	7	3	7	4
Common carp	8	8	8	5	6	2	6	2	7	4
Thai sarputi	4	4	6	3	2	1	2	1	3	2
Sub-total	26	**23**	**34**	**19**	**11**	**5**	**15**	**7**	**22**	**12**
Catfish										
Pangasius	10	9	1	0	0	0	0	0	4	2
Other catfish	3	4	0	0	3	3	1	1	2	2
Sub-total	**13**	**13**	**1**	**1**	**3**	**3**	**2**	**1**	**6**	**4**
Other fish	5	8	6	5	14	15	8	7	7	8
Fish total	**100**	**100**	**88**	**57**	**68**	**37**	**70**	**36**	**84**	**53**
Crustacean										
Shrimp	0	0	0	0	24	50	18	37	9	24
Prawn	0	0	12	43	0	0	8	21	5	18
Other crustacean	0	0	0	0	8	12	4	7	2	5
Crustacean total	**0**	**0**	**12**	**43**	**32**	**63**	**30**	**64**	**16**	**47**

enhanced survival rates and reduced shrimp disease risk (Karim et al., 2012), suggest a gap between recommended practices and on-farm implementation.

Most fish seeds (86 % by volume) were sourced from mobile traders (p*atilwala*), while smaller proportions came from hatcheries (7.7 %), large traders (4.4 %), nurseries (1.1 %), and other sources (0.9 %). This preference for mobile traders may be due to their convenience, small purchase volumes, multiple stocking practices, and disease risk management. In contrast, crustacean PLs were mainly bought from large seed traders (75 % by volume), followed by mobile traders (22 %), hatcheries (2.0 %), and nurseries (0.9 %). The reliance on large traders reflects logistical challenges in transporting delicate crustacean PLs, consistent with Ali et al. (2023a), who noted that hatcheries supply large seed traders, who then sell to farmers.

The survey revealed that 27 % of farmers received seeds as in-kind credit, with this being more common for crustacean seeds (27 % of total volume) than fish seeds (9.5 % of total volume). The meso-scale survey showed that in-kind credit arrangements occasionally resulted in seed prices being 3–5 % higher than cash purchases, aligning with findings by Choudhury and Islam (2015) on agricultural input pricing. However, interest was not always applied, as this varied based on the nature of the relationships between farmers and traders.

3.3.2.2. Feed and non-feed inputs. The first reported use of any feed in aquaculture was in 1985, when a few farms began to apply non-formulated feeds such as rice bran and broken rice. Farmers started to use commercial formulated feeds in 1999. Use of non-formulated feeds increased more quickly than formulated feed from 1999 to 2010, whereafter use of formulated feeds increased most rapidly (Fig. 3). Fifty percent of surveyed farmers using rice bran in 2020 had started to do so on or after 2009, whereas about half of those using floating formulated feeds did so from 2015 onwards.

Almost all farmers (95 %) used some form of supplementary feed in 2020 (Table 6) and among these farms, the majority (59 %) used both formulated and non-formulated feeds, particularly in farms producing fish alongside prawn (PF, 71 %) or fish only (FO, 56 %). Farms producing shrimp, either in combination with prawn and fish (PSF; 50 %) or with fish only (SF; 37 %) were less likely to use both types of feed.

Exclusive use of non-formulated feeds was more common on farms producing shrimp (SF, 43 %; PSF, 41 %) followed by FO (32 %) and PF (18 %) farms, indicative of the traditional semi-intensive management practices in shrimp farming (Jahan et al., 2015). Conversely, the exclusive use of formulated feed remained rare, accounting for only 4 % of surveyed farms, suggesting limited adoption of highly intensive aquaculture in southern Bangladesh (Ali et al., 2022). The share of farms using formulated and non-formulated feeds has increased rapidly between 2013 and 2020 from 43 % to 63 % and 56 % to 92 %, respectively.

The average volume of feed used in 2020 was 3.24 t/ha (Table 6), representing a 30–38 % increase since 2013, signifying an ongoing process of rapid intensification in fish production in southern Bangladesh. During this period, many farmers have shifted from traditional extensive to semi-intensive production while others have upgraded to more intensive production through increasing formulated feed use, but without abandoning cheaper non-formulated feeds. The increasing rates of feed use also reflect a shift in the production system in the study zone moving away from traditional shrimp and fish polyculture to include more prawn and diversified fish species that require formulated diets to attain optimal growth. The application rate of formulated and non-formulated feed was highest in the FO farms (2.12 and 2.59 t/ha, respectively) and lowest in the SF farms (0.25 and 0.56 t/ha, respectively). This pattern corresponds with findings from other surveys on aquaculture in southern Bangladesh (Jahan et al., 2015; Hernandez et al., 2018).

Formulated feed accounted for 39 % of total feed used across the farm categories, slightly lower than the figure reported by Ali et al. (2023b) for the fish feed supply segment in Bangladesh (47 % of total feed). Among the formulated feed used by farmers, floating feed

Table 5
Seed procurement and use practices by farmers.

Variables	Farmer category				
	FO	PF	SF	PSF	Overall
Seed stocked by type (%)					
Tilapia	79	50	90	74	72
Carp	100	100	100	100	100
Catfish	32	10	2	2	16
Crustacean	0	100	100	100	67
Seed stocking density					
Fish (kg/ha)	761	429	290	259	498
Crustacean (no./ha)	0	19,163	223,336	196,197	80,698
Mean seed stockading frequency					
Fish	1.3	1.2	1.4	1.4	1.3
Tiger shrimp	–	–	6.6	6. 3	6.4
Freshwater prawn	–	1.4	–	1.3	1.3
Nursing crustacean PL prior to stock (%)		17	11	23	19
Farmers stocking PCR tested PL (%)			11	16	15
Mean volume of PCR tested PL stocked (%)			52	57	57
Reason for not stocking PCR tested PL (%)					
Never heard of PCR tested PL			7	28	24
Too expensive			46	27	31
Ineffective at preventing disease			7	6	6
Not available here			21	26	25
Do not know			20	11	13
Farmers stocking SPF tested PL (%)			1.5	1.4	1.5
Mean volume of SPF tested PL stocked (%)			10	19	17
Reason for not stocking SPF tested PL (%)					
Never heard of PCR tested PL			16	37	33
Too expensive			30	22	24
Ineffective at preventing disease			3	6	5
Not available here			41	37	38
Do not know			23	14	16
Share of fish seed purchase by suppliers (%)					
Hatchery	14	3.9	12	2.0	7.7
Nursery	1.0	2.3	1.8	0.1	1.1
Mobile seed trader	83	87	85	89	86
Large seed trader	1.7	4.4	1.0	8.3	4.4
Others	0.3	2.4	0.2	0.6	0.8
Share of crustacean seed purchase by suppliers (%)					
Hatchery		1.3	1.0	2.4	2.0
Nursery		0	2.2	0.6	1.0
Mobile seed trader		6.7	11	28	22
Large seed trader		92	86	69	75
Others					
Farmers getting seed as in-kind credit (%)	11	24	43	46	27
Share of fish seed getting as in-kind credit (%)	5.5	10	6.8	15	9.1
Share of crustacean seed getting as in-kind credit (%)		16	29	30	27

contributed 58 % of the total (Table 6). The meso-scale results suggested that the volume of floating feed used is growing more rapidly than sinking feeds. This observation is consistent with Sarwer (2021) estimation that floating feed constituted 60 % of the total national formulated feed production in Bangladesh in 2020. The production of floating feed has notably increased over the last decade and this shift has likely contributed to higher levels of farm productivity and efficiency in aquaculture as floating feed generally has better digestibility and feed conversion ratios compared to sinking feed, ceteris paribus.

The use of non-feed inputs in aquaculture, including organic and inorganic fertilizers such as urea and TSP, has markedly increased since 1985, accelerating notably from 2000 onward. Fertilizer use rose faster than aquaculture chemicals until 2010, after which chemical use saw the most rapid growth (Fig. 4). Fertilizer application was more prevalent in shrimp farms, whether combined with prawn and fish or used solely for fish. This trend aligns with previous studies on aquaculture practices in Bangladesh (Rico et al., 2013). Nearly all farmers (93 %) used disinfectants for water and soil treatment in 2020, reflecting improved management practices compared to 82 % in 2013. Pesticide use was highest in prawn and shrimp farms (20–26 %), primarily for eliminating unwanted and other harmful aquatic organisms before stocking (Rico et al., 2013). There was a slight increase in the use of vitamins and probiotics between 2013 and 2020, indicating ongoing intensification of farming practices (Emerenciano et al., 2022; Rohani et al., 2022).

The majority of feed (92 %) was purchased, with only 8 % produced by farmers, mainly from rice products. Formulated feeds were primarily sourced from dealers (54 %), while non-formulated feeds were mainly bought from retailers (65 %). Fertilizers and aquaculture medicines were mostly purchased from local shops (73 %), with additional sources including specialized aquaculture shops (14 %) and agricultural input shops (13 %). This distribution network highlights the accessibility of inputs for rural farmers. Most input deliveries (72 %) were made by human-haul or engine van, and 78 % of these deliveries relied on rented vehicles, with transport costs representing only 1.7 % of total input expenses. Additionally, 24 % of farmers received inputs as in-kind credit, sometimes at prices 1.5 % higher than cash purchases, though interest was not always charged, depending on the relationship between farmers and traders.

3.3.3. *Farmer sales behavior*

Nearly all farms (96 %) sold part of their fish and/or crustaceans, achieving a marketed surplus of 71 % (Table 7), highlighting a high level of commercial activity. About 90 % of the products were sold to local markets, while 7 % were sold directly at the farmgate to assemblers. Most fish (89 %) and prawn (91 %) were auctioned, with shrimp also commonly sold through auctioneers (56 %) and assemblers or depots (44 %). Farmers typically transported shrimp to auction markets in larger quantities at the end of the production cycle for better prices. This behavior aligns with findings from Van Houten et al. (2019) and Pham et al. (2021), which indicate that farmers are prepared to travel greater distances to achieve higher returns.

Farmers generally arranged their own transportation, using human-hauled vans (81 %) and autorickshaws (13 %), with 89 % of vehicles rented, indicating reliance on third-party logistics (3PLs) for their products' transportation requirements. Transportation costs were low, under 1 % of the total product value. Only 4 out of 721 farmers reported losses, spoilage, or wastage during transport, averaging just 0.52 % of the total volume sold, conditional on losing stock. This minimal loss is attributed to factors such as the proximity of farms to markets, effective use of foam boxes and plastic crates, and the efficiency of 3PL services, alongside a trend toward marketing fish live.

3.3.4. *Financial management*

Farmers employed diverse funding sources for their aquaculture operations (Table 8). About 26 % of farmers sought loans from at least one lender, with borrowing more common in crustacean farms (26–42 %) than fish farms (13 %). Loans primarily covered operational costs, including seeds, feeds, labor, and repairs, with an average loan amount of USD 909, showing no significant variation ($p \geq 0.05$) across farm types.

Self-organized societies and microfinance providers were key credit sources, used by 41 % and 37 % of farmers, respectively. These institutions are acknowledged for their extensive presence in rural areas and simplified application processes, enhancing accessibility for farmers (Jahan et al., 2015). Private and government banks also played

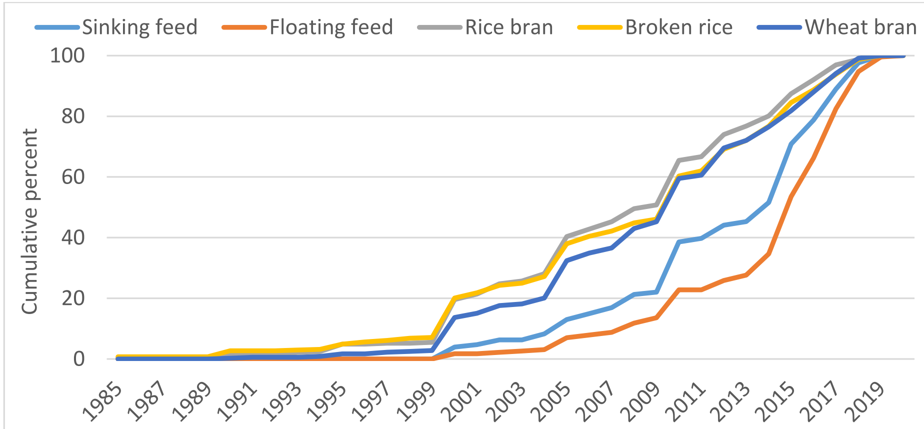

Fig. 3. Cumulative share of farms using selected feeds by year of first use (%).

significant roles, serving 17 % and 12 % of farmers. This indicates that farmers have access to formal credit through such institutions (Sabur et al., 2010; Sarwer, 2021). The average interest rate was relatively low at 13 % per annum, indicating good access to formal and semi-formal financial institutions (Jahan et al., 2015). Informal sources, such as relatives/friends (6 %) and moneylenders (5 %), were less common but often associated with higher interest rates and greater risks. A small proportion of farmers (9 %) invested personal funds, primarily from remittances, with FO farms slightly more likely to use remittances (13 % vs. 6–8 % in other farms). The average remittance was USD 1791, showing no significant difference ($p \geq 0.05$) across farm types.

Only 17 % of farmers received tied-credit ("dadon"), mainly from auctioneers (60 %) and depots (38 %). This is lower compared to other crop sectors in Bangladesh and India (Reardon et al., 2012). The meso-scale survey revealed a marked decline in the reliance on *dadon* among aquaculture farmers, driven by the availability of more favorable alternatives, including a broader range of buyers and access to formal credit options. This reduction in the importance of *dadon* is also associated with lower fish prices and improved access to formal financial sources (Alam et al., 2021; Jahan et al., 2015). The average *dadon* was USD 451/year, with no explicit interest charged and consistent commission rates (2.9 % vs. 3.1 %). Most *dadon* was repaid within a year through incremental payments, but 28 % was partially settled and carried over.

3.4. Performance

The performance of the farming segments within the aquaculture value chain was evaluated, focusing on employment generation, financial outcomes, and the impact of disease outbreaks.

3.4.1. Employment generation

Aquaculture in the region shows extensive family involvement, with 99 % of farmers utilizing male family members (an average of 1.5 members) and 62 % involving female family members (an average of 1.1 members) (Table 9). This highlights the prevalence of family-owned operated aquaculture enterprises, a common practice in numerous aquaculture-producing countries (Kumar et al., 2008; Macfadyen et al., 2012; Msuya and Hurtado, 2017; Belton et al., 2018; Joffre et al., 2021). Most farmers (82 %) employed casual male labor, averaging 3.7 workers, while only 15 % used casual female labor, with an average of 3.0 workers. A small percentage (4 %) of farmers hired permanent male workers, averaging 1.0 worker per farm, but none reported employing permanent female labor.

Casual male workers earned an average daily wage of USD 3.71, which is higher than the national average daily wage rate of USD 2.14 for agricultural work in Bangladesh (BBS, 2022b). However, a significant gender wage gap ($p \leq 0.05$) was observed, with women earning 43 % less than men, consistent with previous findings in the sector (Belton et al., 2014; Jahan et al., 2015; Kruijssen et al., 2021). Permanent workers received an average monthly wage of USD 62, slightly above the national minimum wage for agricultural activities (BBS, 2022b).

Aquaculture production generated an average of 378 person-days per ha, equating to 1.45 full-time equivalent (FTE) jobs per ha (Table 9), based on a 2080-h work year. This employment rate is double that of rice production, which typically requires 142 to 189 (Belton et al., 2014; Gurung et al., 2016). In total, 830 FTE jobs were created among 721 fish farmers, with 73 % family labor, 19 % casual labor, and 8.4 % permanent labor. Notably, 25 % of these jobs were filled by individuals aged 29 or younger, indicating aquaculture's potential for youth employment in Bangladesh. This level of youth employment is similar to the average of 19 % observed in agrifood production systems across Asia (Dolislager et al., 2021). Despite this, employment was predominantly male (90 %), with women representing only 10 % of the workforce, a rate lower than the 37 % reported in other studies on aquaculture in Bangladesh (Kruijssen et al., 2021).

We estimate the total number of FTE jobs created by aquaculture farming in the seven southern districts of Bangladesh. To do so, we estimated the average number of FTE jobs created per ha of aquaculture area, multiplied by the total area of aquaculture farms in these regions as reported in the Department of Fisheries (2022). Aquaculture farming contributed to an estimated 401,536 full-time equivalent (FTE) jobs across the seven surveyed districts (Table 10), significantly surpassing those created by fish hatcheries (2491 FTEs), fish trading (41,831 FTEs), and feed trading (43,937 FTEs) business in the same area (Ali et al., 2023a; Ali et al., 2023b). Fish production accounted for the highest employment opportunities, with 335,497 FTEs compared to crustaceans with 66,039 FTEs. These FTEs were distributed across various categories, including 292,769 family labor FTEs, 75,036 casual labor FTEs, and 33,731 permanent labor FTEs. Furthermore, there were 102,116 youth FTEs and 299,420 non-youth FTEs, as well as 361,498 men FTEs and 40,038 women FTEs.

3.4.2. Financial performance

Aquaculture production costs were significantly higher ($p \leq 0.05$) in FO (USD 3733 ha^{-1}) and PF (USD 3603 ha^{-1} $year^{-1}$) farms compared to PSF (USD 2899 ha^{-1} $year^{-1}$) and SF (USD 2398 ha^{-1} $year^{-1}$) farms (Table 11). This disparity is primarily due to variable expenses, which make up 90 % of total costs, aligning with previous findings that variable costs in aquaculture in Bangladesh range from 83 % to 96 % (Ahmed et al., 2010; Karim et al., 2014; Gurung et al., 2016). Key variable costs included feed (49 %), seed (24 %), and labor (10 %), consistent with previous studies on cost structures in fish and crustacean

Table 6
Feed and non-feed procurement and use practices by farmers.

Variables	Farmer category				
	FO	PF	SF	PSF	Overall
Feed use					
Farmers using any feed (%)	95	100	83	93	95
Farmers using no feed (%)	5	0	11	7	5
Farmers using only formulated feed (%)	6	2	3	2	4
Farmers using only non-formulated feed (%)	32	18	43	41	33
Farmers using formulated & non-formulated feed (%)	56	81	37	50	59
Total feed use (t/ha)	4.71	3.51	0.81	1.77	3.24
Floating formulated feed use (t/ha)	1.50	0.42	0.07	0.15	0.74
Sinking formulated feed use (t/ha)	0.62	0.83	0.19	0.26	0.53
Rice products use (t/ha)	1.25	0.93	0.38	0.45	0.87
Wheat products use (t/ha)	0.57	0.52	0.06	0.33	0.45
Other non-formulated feed use (t/ha)	0.77	0.82	0.12	0.57	0.67
Formulated feed in total feed use (%)	45	35	31	23	39
Floating formulated feed in total feed (%)	32	12	8	9	23
Floating feed in total formulated feed (%)	71	33	26	37	58
Purchased of formulated feed by supplier					
Feed mill (%)	1	0	0	1	1
Feed dealer (%)	67	40	29	47	54
Feed retailer (%)	32	60	71	51	45
Purchased of non-formulated feed by supplier					
Feed mill (%)	2	2	0	4	2
Feed dealer (%)	16	33	1	34	28
Feed retailer (%)	77	63	99	56	65
Others (%)	6	2	0	6	5
Non-feed use					
Farmers using organic fertilizer (%)	28	27	49	43	34
Farmers using inorganic fertilizer (%)	58	63	92	76	67
Mean volume of organic fertilizer used (kg/ha)	3434	4140	1774	1839	2763
Mean volume of inorganic fertilizer used (kg/ha)	453	443	200	198	337
Farmers using antibiotics (%)	0.4	1.2	0.0	0.5	0.6
Farmers using disinfectants (%)	90	97	98	92	93
Farmers using pesticides (%)	8.8	22	20	26	18
Farmers using vitamin (%)	4.2	15	4.9	12	9.0
Farmers using probiotics (%)	1.1	9	16	9.5	6.7
Mean volume of aquaculture chemical used (kg/ha)	363	211	165	177	240
Purchased of non-feed inputs by supplier (%)					
Agricultural input dealer	14	8	11	16	13
Local village shop	76	67	81	71	73
Aquaculture medicine shop	9	25	7	13	14
Farmers getting feed as in-kind credit (%)	17	32	13	32	24
Feed deliveries made by vehicle type (%)					
Human-haul or engine van	61	83	36	77	72
Bicycle	12	9	32	16	14
Autorickshaw	25	6	18	3	11
Motorcycle	1	1	14	3	2
Other	0	1	0	1	1
Deliveries made by own vehicle (%)	20	17	49	24	22
Deliveries made by rented vehicle (%)	80	83	51	76	78

production (Karim et al., 2014; Jahan et al., 2015). FO farms had the highest feed costs (60 %), while SF farms had the highest seed costs (37 %).

Gross annual revenue across farm categories ranged from USD 4862 to 6874 ha^{-1} (Table 11). A significant 90 % of farmers reported profits, with an average gross margin of USD 3267 ha^{-1} and a net margin of USD 2939 ha^{-1}, both of which are notably higher than those of rice farmers in Bangladesh (Gurung et al., 2016; Akter et al., 2019; Rahman et al., 2022). The average benefit-cost ratio (BCR) for aquatic food production was 1.98, nearly doubling the return on investment. This is significantly higher than the BCR of 1.07 for rice production in northern Bangladesh (Rahman et al., 2022) and the 0.9 to 1.5 range reported for rice production in southern Bangladesh (Gurung et al., 2016). Akter et al. (2019) reported BCRs of 1.19 for small, 1.40 for medium, and 1.43 for large rice farmers. PSF (2.29) and SF (2.17) farms had notably higher BCRs compared to PF (1.73) and FO (1.91) farms, due to their lower production costs.

3.4.3. Impact of diseases on aquaculture production

The highest incidence of disease in the 2020 production cycle was reported in SF farms (56 %), followed by PSF (48 %), PF (25 %), and FO (11 %) farms (Fig. 5). White Spot Disease (WSD), a major issue in shrimp farming (Karim et al., 2012), was reported by 38 % of PSF and 36 % of SF farmers. Antenna broken, affecting freshwater prawns (MacRae et al., 2002; Rico et al., 2013), was noted by 13 % of PF, 9 % of PSF, and 3.3 % of SF farmers.

Disease frequency was notably higher ($p \leq 0.05$) in shrimp farms (SF, 1.73 and PSF, 1.55) compared to fish (FO, 1.24) and prawn farms (PF, 1.05). Of those reporting diseases, 55 % did not use treatments, while 45 % applied various management strategies, including disinfectants and antibiotics. Shrimp farms experienced higher ($p \leq 0.05$) mortality rates (PSF, 25 % and SF, 22 %) compared to prawn (PF, 3.2 %) and fish farms (FO, 1.8 %). Economic losses were also significantly higher ($p \leq 0.05$) in SF (USD 799/ha) and PSF (USD 493/ha) farms compared to FO (USD 83/ha) and PF (USD 75/ha) farms. These findings highlight the increased vulnerability of shrimp farms to disease outbreaks compared to prawn and fish, or exclusively fish farmers. To address this, shrimp farmers are integrating prawn and crustacean species with fish, aiming to mitigate the impact of diseases on their operations.

4. Conclusions

The aquaculture production segment in southern Bangladesh is experiencing substantial growth and transformation, yet its intricacies and organizational framework remain underexplored. A comprehensive understanding of this sector's dynamics requires a deep dive into its structural, conduct, and performance aspects. The survey results offer valuable insights into the evolving nature and efficiency of the aquaculture production segment, summarized as follows:

First, the number of farmers and aquaculture waterbodies grew by less than 15 % over the past decade, indicating that initial expansion is nearly complete. The emphasis has now shifted from expanding horizontally to intensifying production systems, with feed use rising by 30–38 % over the same period, indicating a rapid intensification of fish production in southern Bangladesh.

Second, there has been a rapid diversification in farmed aquatic species, driven by mitigate disease risks, environmental conditions, market demands, and opportunities and create alternative income sources. This diversification has led to an increased production of fish intended for the domestic market, contrasting with the previous focus on export-oriented crustaceans.

Third, shrimp production is susceptible to diseases compared to fish and prawn who demonstrate more resilience. However, there is limited adoption of measures to improve crustacean survival, such as nursing PL before stocking (19 %), with minimal use of PCR or SPF tested PL. The study recommends the adoption of Better Management Practices (BMPs) guidelines for improving farm productivity and disease management.

Fourth, disease outbreaks have prompted adaptations in aquaculture systems, including integrating freshwater prawns into shrimp farming and emphasizing fish production within crustacean systems to mitigate disease on farm operation. This adaptation has led to a rise in fish as the

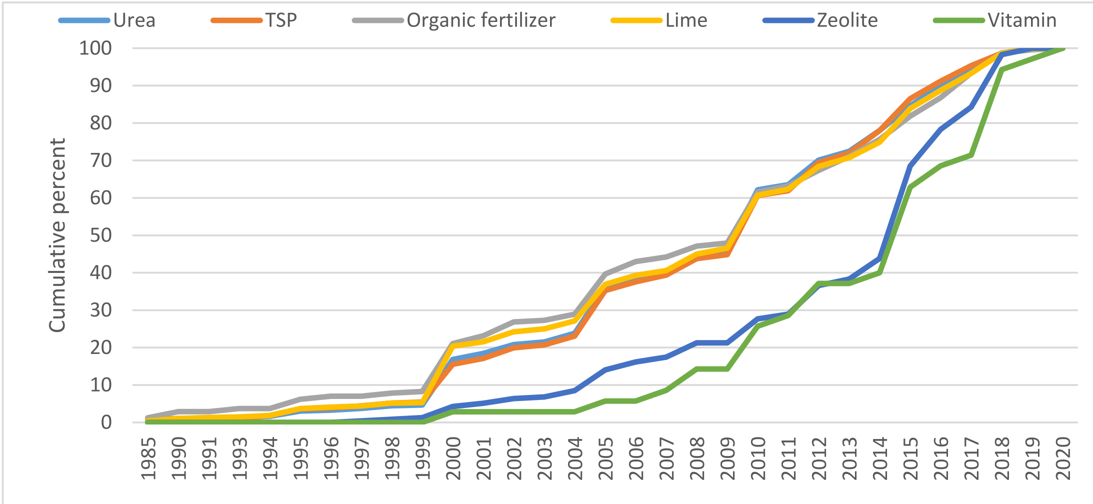

Fig. 4. Cumulative share of farms using non-feed inputs by year of first use (%).

Table 7
Fish marketing practices reported by farmers.

Variables	Farm category				
	FO	PF	SF	PSF	Overall
Farmers selling aquatic foods (%)	91	99	98	100	96
% of harvested products sold	61	74	82	80	71
Distribution of clients for fish (%)					
Auctioneer	78	98	95	96	89
Assembler/depot	14	1	4	2	7
Consumer	4	1	0	0	2
Others	4	0	1	2	2
Distribution of clients for prawn (%)					
Auctioneer	0	97	0	87	91
Assembler/depot	0	2	0	13	8
Consumer	0	1	0	0	1
Distribution of clients for shrimp (%)					
Auctioneer	0	0	48	59	56
Assembler/depot	0	0	52	41	44
Location of clients for aquatic foods (%)					
Same village	17	2	23	13	13
Same union	31	33	30	16	26
Same upazila	42	42	40	35	40
Same district	9	23	7	35	21
Other districts	1	0	0	1	0
Transportation supports provided by (%)					
Farmer	81	99	100	100	93
Traders	19	1	0	0	7
Type vehicle used (%)					
Human hauled van	76	84	77	86	81
Autorickshaw	21	10	17	7	13
Motorcycle	2	5	4	7	5
Bicycle	1	1	2	0	1
Deliveries made by own vehicle (%)	20	7	11	6	11
Deliveries made by rented vehicle (3PLS) (%)	80	93	89	94	89
% of farmers reporting product loss or waste	0	0	2	1	1
% of total volume sold lost or wasted, (conditional on reporting loss/waste)	n/a	n/a	1.4	0.22	0.52
Mode of payment- received advanced (%)	0	0	0	0.47	0.14
Mode of payment-received delayed (%)	2.5	4.2	3.3	4.7	3.6
Mode of transaction (%)					
Cash	100	100	100	100	100
Bank transfer	0	0	0	0	0
Mobile money	0	0	0	0	0

Table 8
Farmers access of finance to manage aquaculture activities.

Variables	Farm category				
	FO	PF	SF	PSF	Overall
% of farmers receiving credit	13	26	36	42	26
Mean volume of credit received (USD)	1086	538	900	1015	909
Mean interest rate per year (%)	13	13	11	13	13
Sources of credit (%)					
Cooperative	42	40	32	44	41
Microfinance	37	40	32	41	39
Government bank	18	9	23	19	17
Private bank	11	2	23	14	12
Relatives/friends	3	12	5	5	6
Informal lender	5	5	9	5	5
% of farmers used remittances in aquaculture	13	6	8	7	9
Mean volume of remittance received (USD), (conditional)	2111	1128	1189	1588	1791
% of farmers received dadon in 2020	8	11	33	29	17
Mean amount of dadon received (USD), conditional	560	329	666	366	451
Dadon received as % of total farm sales (conditional)	51	26	23	21	27
Dadon received as % of total farm sales (unconditional)	3.8	2.8	7.7	6.1	4.7
Dadon received from:					
Auctioneer	73	69	50	57	60
Depot	20	23	50	43	38
Assembler	7	8	0	0	2
% of farmers receiving dadon obligated to sell to provider	100	100	100	100	100
% of farmers receiving dadon paying an explicit interest rate	0	0	0	0	0
Dadon repayment system (%)					
Paid off in full through partial payments	60	62	61	67	64
Paid off partially and rolled over	27	15	33	31	28
Paid off in full at end of season	13	23	6	0	7
Never repaid any	0	0	0	2	1
Commission rate (% of sales value)					
Paid to auctioneers by dadon recipients	2.8	3.6	2.6	2.8	2.9
Paid to auctioneers by dadon non-recipients	3.2	3.3	2.6	2.9	3.1

predominant aquaculture crop and increased reliance on supplementary feeds, particularly commercial floating feeds.

Fifth, tied output-credit was once common in southern Bangladesh (Guimarães, 1989) but is now rare. Only 17 % of farmers receive such credit from traders, amounting to 4.7 % of their sales. This decline reflects better options available to farmers, such as buyers and formal credit.

Table 9
Employment characteristics for fish farming.

Variables	Farm category				
	FO	PF	SF	PSF	Overall
Family labor					
Male family labor (% of farmers using)	98	99	100	99	99
Average number of male family workers	1.4	1.5	1.5	1.5	1.5
Female family labor (% of farmers using)	73	52	61	56	62
Average number of female family workers	1.1	1.1	1.1	1.1	1.1
Casual hired labor					
Male casual labor (% of farmers using)	67	96	90	91	82
Average number of male causal workers	3.0	4.0	4.5	3.8	3.7
Average wage of male casual worker (USD/day)	3.48	4.06	3.29	3.77	3.71
Female casual labor (% of farmers using)	2.1	2.4	44	35	15
Average number of female causal workers	1.3	2.0	3.5	2.9	3.0
Average wage of female casual worker (USD/day)	2.36	2.51	2.05	2.08	2.10
Permanent hired labor					
Male permanent labor (% of farmers using)	3.5	1.8	8.2	5.2	4.0
Average number of male permanent workers	1.0	1.0	1.2	1.0	1.0
Average wage of male permanent worker (USD/month)	48	71	94	61	62
Female permanent labor (% of farmers using)	0	0	0	0	0
Overall employment generation					
Average labor-day per ha of aquatic foods products	343	317	391	469	378
Average FTE jobs per ha	1.32	1.22	1.50	1.81	1.45
Total FTE jobs created by sample farmers	93	116	143	338	690
FTE job distribution by products (%)					
Fish	100	88	68	70	84
Crustaceans	0	12	32	30	16
Family FTE jobs created	78	71	67	73	73
Casual hired FTE jobs created	16	24	24	16	19
Permanent hired FTE jobs created	6.0	4.3	9.0	10	8.4
FTE jobs created for men	81	92	88	93	90
FTE job created for women	19	7.7	12	7.5	10
FTE job created for youth (≤29 years)	23	27	20	29	25
FTE job created for non-youth (≥30 years)	77	73	80	71	75

Sixth, transportation practices are effective, as only a small percentage of farmers (0.55 %) reported minimal losses (0.52 %) during transport. This suggests well-managed transportation processes and efficient use of logistics services.

Seventh, aquaculture in southern Bangladesh, primarily family-owned, provides 401,536 full-time equivalent jobs. The sector employs a diverse range of workers, including family members, casual, and permanent staff, across all age groups. This indicates significant job opportunities, particularly for the youth.

Finally, aquaculture systems exhibit profitability and resilience despite challenges, attributed to their diversity and adaptability. To enhance the sustainability and resilience of the aquaculture sector in southern Bangladesh, policymakers should prioritize promoting advanced production technologies, Better Management Practices (BMPs) for improved farm productivity and disease management, and supporting financial accessibility through enabling policies, regulations, public investments, and infrastructure development.

Table 10
Total FTE jobs created by fish farming in southern Bangladesh.

Variables	Farm category				
	FO	PF	SF	PSF	Overall
Total FTE jobs created	54,157	67,607	83,221	196,552	401,536
FTE job distribution by product					
Fish	53,716	80,072	48,153	129,714	335,497
Crustaceans	0	10,982	22,714	56,186	66,039
FTE job distribution by type of labor					
Family labor	42,450	48,337	55,666	143,687	292,769
Causal labor	8448	16,342	20,078	32,331	75,036
Permanent labor	3258	2928	7477	20,533	33,731
FTE job distribution by gender					
Men	43,947	62,398	73,371	181,823	361,498
Women	10,210	5209	9850	14,729	40,038
FTE job distribution by age					
≤29 years (youth)	12,416	18,187	16,894	57,103	102,116
≥ 30 years (non-youth)	41,740	49,420	66,326	139,448	299,420

5. Limitations of the study

Despite the extensive survey and rigorous methodology employed in this study, several limitations should be acknowledged.

Firstly, the study's focus on seven key districts, while important for aquaculture, may not fully reflect the diverse practices and challenges in other regions of Bangladesh, limiting the generalizability of the findings to the broader national context.

Secondly, the survey data, gathered between November 2020 and February 2021 during the COVID-19 pandemic, might reflect the pandemic's effects on aquaculture operations and farmers' responses, potentially skewing results due to the period's unique conditions.

Thirdly, despite attempts to replicate the 2013 survey's sampling approach, replacing closed or unavailable farms with new ones could introduce biases. These new farms may have different characteristics, affecting the comparability of the findings over time.

Lastly, the study's analysis is confined to the available data and measured variables, potentially missing other critical factors affecting aquaculture, such as climate change, market dynamics, and policy shifts. These limitations highlight the need for further research to fill these gaps and offer a more complete understanding of the sector's challenges and opportunities.

Ethics statement

The research design was reviewed by Michigan State University Institutional Review Board (MSU Study ID: STUDY00003689). The study was determined to be exempt from IRB review on July 10, 2020.

CRediT authorship contribution statement

Hazrat Ali: Writing – original draft, Validation, Supervision, Formal analysis, Data curation, Conceptualization. **Mohammad Mahfujul Haque:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Khondker Murshed-e-Jahan:** Writing – review & editing, Supervision, Project administration, Investigation.

Declaration of competing interest

The authors have no competing interests to declare regarding the manuscript "Transformation of the farm segment of the aquaculture value chain in southern Bangladesh."

Table 11
Annual cost and profit margin of aquaculture production.

Cost and return (USD/ha/year)	Farm category									
	FO		PF		SF		PSF		Overall	
	Mean cost	% of cost	Mean cost	% of cost	Mean cost	% of cost	Mean cost	% of cost	Mean cost	% of cost
Variable cost (VC)										
Seed	703	19	797	22	883	37	880	30	791	24
Feed	2252	60	1686	47	628	26	1032	36	1628	49
Labor	238	6.4	442	12	286	12	339	12	318	10
Fertilizer	92	2.5	88	2.4	73	3.0	70	2.4	83	2.5
Chemicals	70	1.9	62	1.7	56	2.3	47	1.6	60	1.8
Harvesting and marketing	54	1.5	72	2.0	38	1.6	57	2.0	58	1.7
Miscellaneous	82	2.2	80	2.2	95	3.9	71	2.5	79	2.4
Sub-total	**3492**	**94**	**3226**	**90**	**2059**	**86**	**2497**	**86**	**3019**	**90**
Fixed cost (FC)										
Land leased	93	2.5	261	7.3	193	8.1	267	9.2	191	5.7
Depreciation	148	4.0	115	3.2	146	6.1	135	4.7	137	4.1
Sub-total	**241**	**6.5**	**376**	**10**	**339**	**14**	**402**	**14**	**328**	**10**
Total cost (TC) = VC + FC	**3733**	**100**	**3603**	**100**	**2398**	**100**	**2899**	**100**	**3346**	**100**
Mean gross revenue	6874		5856		4862		6241		6285	
Mean gross margin	3383		2629		2803		3744		3267	
Mean net margin	3142		2253		2464		3341		2939	
Benefit-cost ratio (BCR)	**1.91**		**1.73**		**2.17**		**2.29**		**1.98**	

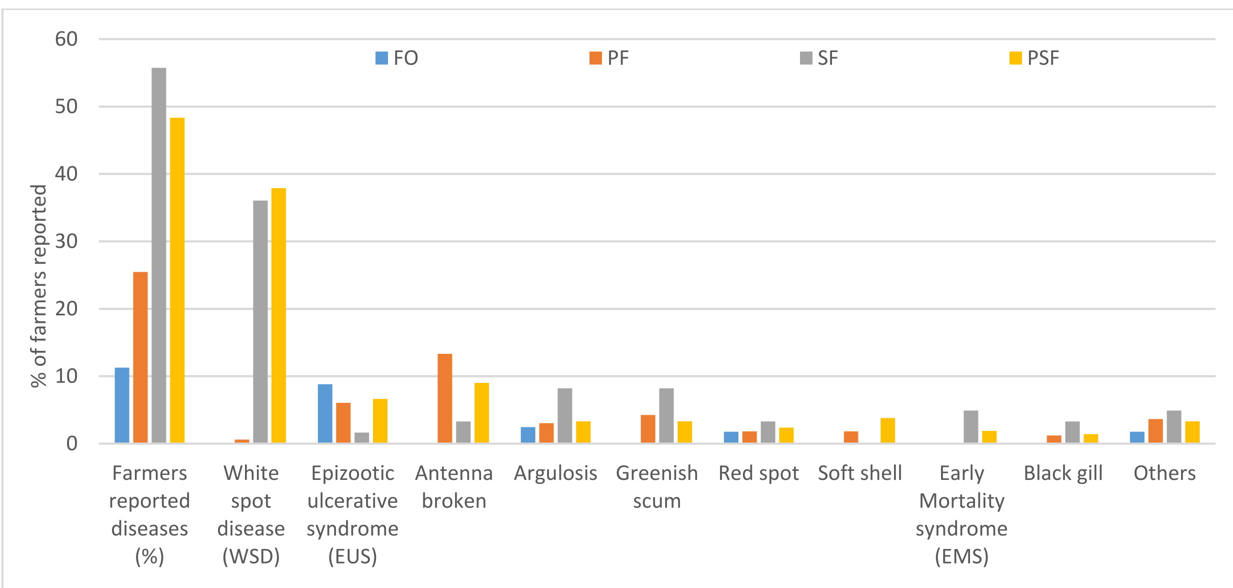

Fig. 5. The share of farmers (%) reported different types of diseases for their farms.

Data availability

Data will be made available on request.

Acknowledgments

This research was made possible by the Feed the Future Innovation Lab for Fish, through the United States Agency for International Development (USAID). The Feed the Future Innovation Lab for Fish is managed by Mississippi State University through an award from USAID (Award No. 7200AA18CA00030; M. Lawrence, PI) and provides support to this project (Grant No. 193900.312455.12B; Belton, PI; Haque, PI). This work was also implemented as part of the CGIAR Initiative on Securing the Food Systems of Asian Mega-Deltas for Climate and Livelihood Resilience (INIT-18), which is carried out with support from funders through their contributions to the CGIAR Trust Fund. For details please visit: https://www.cgiar.org/funders/.

References

Ahmed, N., 2013. Linking prawn and shrimp farming towards a green economy in Bangladesh: confronting climate change. Ocean Coast. Manag. 75, 33–42. https://doi.org/10.1016/j.ocecoaman.2013.01.002.

Ahmed, N., Garnett, S.T., 2010. Sustainability of freshwater prawn farming in rice fields in Southwest Bangladesh. J. Sustain. Agric. 34, 659–679. https://doi.org/10.1080/10440046.2010.493397.

Ahmed, N., Alam, M.F., Hasan, M.R., 2010. The economics of sutchi catfish (*Pangasianodon hypophthalmus*) aquaculture under three different farming systems in rural Bangladesh. Aquac. Res. 41, 1668–1683. https://doi.org/10.1111/j.1365-2109.2010.02549.x.

Akter, T., Parvin, M.T., Mila, F.A., Nahar, A., 2019. Factors determining the profitability of rice farming in Bangladesh: profitability analysis of rice farming in Bangladesh. J. Bangladesh Agricult. Univer. 17 (1), 86–91. https://banglajol.info/index.php/JBAU/%20article/view/40668.

Alam, M.F., Palash, M.S., Mian, M.I.A., Dey, M.M., 2012. Marketing of major fish species in Bangladesh: a value chain analysis. A report submitted to Food and Agriculture Organization for the project. In: A Value-Chain Analysis of International Fish Trade and Food Security with an Impact Assessment of the Small-Scale Sector. UNFAO, Rome, Italy.

Alam, A.K.M.N., Rahman, M.K., Zakaria, M.U.M.A., Al-Shahriar, Sarker, F.C., 2021. Nature of dadon and its effect on livelihood status of two fishing communities in

Kishoreganj Haor of Bangladesh. Int. J. Food Sci. Agricult. 5 (1), 140–151. http://www.hillpublisher.com/journals/jsfa/.

Ali, H., Rahman, M.M., Jaman, A., Basak, S.K., Eltholth, M., Murray, F., 2022. Economic performance characterization of intensive shrimp (*Penaeus monodon*) farming systems in Bangladesh. Aquacult. Fish Fisher. 2 (1), 57–70. https://doi.org/10.1002/aff2.29.

Ali, H., Belton, B., Haque, M.M., Murshed-e-Jahan, K., Ignowski, L., 2023a. The structure, conduct, and performance of the hatchery segment of the aquaculture value chain in Bangladesh. Front. Aquacult. 2, 1219458. https://doi.org/10.3389/faquc.2023.1219458.

Ali, H., Belton, B., Haque, M.M., Murshed-e-Jahan, K., 2023b. Transformation of the feed supply segment of the aquaculture value chain in Bangladesh. Aquaculture 576, 739897. https://doi.org/10.1016/j.aquaculture.2023.739897.

Apu, N.A., 2014. Farmed Fish Value Chain Development in Bangladesh: Situation Analysis and Trends. WorldFish/ILRI Project Report. International Livestock Research Institute (ILRI), Nairobi, Kenya.

BBS, 2019. Report on agriculture and rural statistics. In: Agriculture and Rural Statistics Survey (ARSS) Project-2017. Bangladesh Bureau of Statistics (BBS) Statistics and Informatics Division (SID) Ministry of Planning. Bangladesh.

BBS, 2022. Statistical yearbook Bangladesh 2021. In: Statistics & Informatics Division, Ministry of Planning Government of the People's Republic of Bangladesh Dhaka, p. 614. Bangladesh.

BBS, 2022b. Consumer Price Index (CPI), Inflation Rate and Wage Rate Index (WRI) in Bangladesh. National Accounting Wing Bangladesh Bureau of Statistics (BBS) E-27/A, Agargoan, Dhaka-1207, p. 41.

Belton, B., 2016. Shrimp, prawn and the political economy of social wellbeing in rural Bangladesh. J. Rural. Stud. 45, 230–242. https://doi.org/10.1016/j.jrurstud.2016.03.014.

Belton, B., Azad, A., 2012. The characteristics and status of pond aquaculture in Bangladesh. Aquaculture 358-359, 196–204. https://doi.org/10.1016/j.aquaculture.2012.07.002.

Belton, B., Ahmed, N., Jahan, K.M., 2014. Aquaculture, Employment, Poverty, Food Security and Well Being in Bangladesh: A Comparative Study. CGIAR Research Program on Aquatic Agricultural Systems, Penang, Malaysia (Program Report: AAS-2014-39).

Belton, B., Hein, A., Htoo, K., Kham, L.S., Phyoe, A.S., Reardon, T., 2018. The emerging quiet revolution in Myanmar's aquaculture value chain. Aquaculture 493, 384–394. https://doi.org/10.1016/j.aquaculture.2017.06.028.

Bondad-Reantaso, M.G., Subasinghe, R.P., 2013. Enhancing the contribution of small scale aquaculture to food security, poverty alleviation and socio-economic development. In: FAO Fisheries and Aquaculture Proceedings No. 31. FAO, Rome.

Boock, M.V., Marques, H.L.A., Mallasen, M., Barros, H.P., Moraes-Valenti, P., Valenti, W.C., 2016. Effects of prawn stocking density and feeding management on rice–prawn culture. Aquaculture 451, 480–487. https://doi.org/10.1016/j.aquaculture.2015.10.009.

Bosu, A., Das, M., Hossain, S., Moniruzzaman, M., 2016. Evaluation of commercial feed on growth performance of Tilapia (*Oreochromis niloticus*) in Mymensingh. Int. J. Nat. Soc. Sci. 3 (1), 73–82. http://ijnss.org/wp-content/uploads/2020/03/IJNSS-V3I1-4-pp-73-82.pdf.

Boyd, C.E., McNevin, A.A., 2022. Overview of aquaculture feeds: Global impacts of ingredient production, manufacturing, and use. In: Feed and Feeding Practices in Aquaculture, Second edition. Woodhead Publishing Series in Food Science, Technology and Nutrition, pp. 3–28. https://doi.org/10.1016/B978-0-12-821598-2.00003-5.

Bunting, S.W., Kundu, N., Ahmed, N., 2017. Evaluating the contribution of diversified shrimp-rice agroecosystems in Bangladesh and West Bengal, India to social-ecological resilience. Ocean Coast. Manag. 148, 63–74. https://doi.org/10.1016/j.ocecoaman.2017.07.010.

Bush, S., Belton, B., Little, D.C., Islam, M.S., 2019. Emerging trends in aquaculture value chain research. Aquaculture 498, 428–434. https://doi.org/10.1016/j.aquaculture.2018.08.077.

Choudhury, S., Islam, M.S., 2015. Effects of in-kind credit on agricultural input prices: evidence from rural Bangladesh. J. Agric. Econ. 66 (1), 145–160.

Deb, A.K., 1998. Fake blue revolution: environmental and socio-economic impacts of shrimp culture in the coastal areas of Bangladesh. Ocean Coast. Manag. 41, 63–88. https://doi.org/10.1016/S0964-5691(98)00074-X.

Deb, P., Dey, M.M., Surathkal, P., 2022a. Fish price volatility dynamics in Bangladesh. Aquac. Econ. Manag. 26 (4), 462–482. https://doi.org/10.1080/13657305.2021.2008049.

Deb, P., Dey, M.M., Surathkal, P., 2022b. Price transmission and market integration of Bangladesh fish markets. Aquaculture 560, 738592. https://doi.org/10.1016/j.aquaculture.2022.738592.

Dey, M.M., Surathkal, P., 2020. Value chains in aquaculture and fisheries in Bangladesh. In: Transforming Agriculture in South Asia. Routledge, pp. 195–210. https://doi.org/10.4324/9781003024996.

DoF, 2022. Yearbook of Fisheries Statistics of Bangladesh, 2020–21. Fisheries Resources Survey System (FRSS), Department of Fisheries, 38. Ministry of Fisheries and Livestock, Bangladesh, p. 1438.

Dolislager, M., Reardon, T., Arslan, A., Fox, L., Liverpool-Tasie, S., Sauer, C., Tschirley, D.L., 2021. Youth and adult Agrifood system employment in developing regions: rural (Peri-urban to hinterland) vs. Urban. J. Dev. Stud. 57 (4), 571–593. https://doi.org/10.1080/00220388.2020.1808198.

El-Sayed, A.M., Dickson, M.W., El-Naggar, G.O., 2015. Value chain analysis of the aquaculture feed sector in Egypt. Aquaculture 437, 92–101. https://doi.org/10.1016/j.aquaculture.2014.11.033.

Emerenciano, M.G.C., Rombenso, A.N., Vieira, F.D.N., Martins, M.A., Coman, G.J., Truong, H.H., Noble, T.H., Simon, C.J., 2022. Intensification of Penaeid shrimp culture: an applied review of advances in production systems. Nutrit. Breed. Anim. 12, 236. https://doi.org/10.3390/ani12030236.

Engle, C.R., McNevin, A., Racine, P., Boyd, C.E., Paungkaew, D., Viriyatum, R., Tinh, H. Q., Minh, H.N., 2017. Economics of sustainable intensification of aquaculture: evidence from shrimp farms in Vietnam and Thailand. J. World Aquacult. Soc. 48 (2), 227–239. https://doi.org/10.1111/jwas.12423.

FAO, 2022. The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation. FAO, Rome. https://doi.org/10.4060/cc0461en.

Gilson, F., New, M.B., Rodrigues, L.A., Valenti, W.C., 2023. Effect of fish downstream supply chain on wealth creation: the case of tambatinga in the Brazilian Midnorth. Aquac. Int. 31, 1401–1421. https://doi.org/10.1007/s10499-023-01056-0.

Guimarães, J.P.C., 1989. Shrimp culture and market incorporation: a study of shrimp culture in Paddy fields in Southwest Bangladesh. Dev. Chang. 20 (4), 653–682. https://doi.org/10.1111/j.1467-7660.1989.tb00361.x.

Gurung, K., Bhandari, H., Paris, T., 2016. Transformation from Rice farming to commercial aquaculture in Bangladesh: implications for gender, food security, and livelihood. Gend. Technol. Dev. 20 (1), 49–80. https://doi.org/10.1177/0971852415618747.

Haque, M.M., Alam, M.R., Alam, M.M., Basak, B., Sumi, K.R., Belton, B., Jahan, K.M., 2015. Integrated floating cage aquageoponics system (IFCAS): an innovation in fish and vegetable production for shaded ponds in Bangladesh. Aquacult. Report. 2, 1–9. https://doi.org/10.1016/j.aqrep.2015.04.002.

Hasan, M.R., Arthur, J.R., 2015. Aquaculture Seed and Feed Production and Management in Bangladesh – Status, Issues and Constraints. Food and Agriculture Organization of the United Nation, Rome. https://www.fao.org/3/i4945e/i4945e.pdf.

Hernandez, R., Belton, B., Reardon, T., Hub, C., Zhang, X., Ahmed, A., 2018. The quiet revolution in the aquaculture value chain in Bangladesh. Aquaculture 493, 456–468. https://doi.org/10.1016/j.aquaculture.2017.06.006.

HIES, 2023. Household Income and Expenditure Survey 2023. Bangladesh Bureau of Statistics, Ministry of Planning. Government of the People's Republic of Bangladesh, Dhaka, Bangladesh.

Hossain, M.S., Uddin, M.J., Fakhruddin, A.N.M., 2013. Impacts of shrimp farming on the coastal environment of Bangladesh and approach for management. Rev. Environ. Sci. Biotechnol. 12, 313–332. https://doi.org/10.1007/s11157-013-9311-5.

Ignowski, L., Belton, B., Ali, H., Thilsted, S.H., 2023. 2023. Integrated aquatic and terrestrial food production enhances micronutrient and economic productivity for nutrition-sensitive food systems. Nat. Food 4, 866–873. https://doi.org/10.1038/s43016-023-00840-8.

Islam, M., Yasmin, R., 2017. Impact of aquaculture and contemporary environmental issues in Bangladesh. Int. J. Fisher. Aquat. Studi. 5 (4), 100–107.

Jahan, K.M., Belton, B., Ali, H., Dhar, G.C., Ara, I., 2015. Aquaculture Technologies in Bangladesh: an assessment of technical and economic performance and producer behavior. In: WorldFish, Penang, Malaysia. Program Report: 2015-52, p. 123.

Jamal, M.R., Kristiansen, P., Kabir, M.J., de Bruyn, L.L., 2023. Risks and adaptation dynamics in shrimp and prawn-based farming systems in southwest coastal Bangladesh. Aquaculture 562, 738819. https://doi.org/10.1016/j.aquaculture.2022.738819.

Joffre, O.M., Freed, S., Bernhardt, J., Teoh, S.J., Sambath, S., Belton, B., 2021. Assessing the potential for sustainable aquaculture development in Cambodia. Front. Sustain. Food Syst. https://doi.org/10.3389/fsufs.2021.704320.

Karim, M., Sarwer, R.H., Brooks, A.C., Gregory, R., Jahan, K.M., Belton, B., 2012. The incidence of suspected white spot syndrome virus in semi-intensive and extensive shrimp farms in Bangladesh: implications for management. Aquac. Res. 43 (9), 1357–1371. https://doi.org/10.1111/j.1365-2109.2011.02939.x.

Karim, M., Sarwer, R.H., Phillips, M., Belton, B., 2014. Profitability and adoption of improved shrimp farming technologies in the aquatic agricultural systems of southwestern Bangladesh. Aquaculture 428–429, 61–70. https://doi.org/10.1016/j.aquaculture.2014.02.029.

Karim, M., Keus, H.J., Ullah, M.H., Kassam, L., Phillips, M., Beveridge, M., 2016. Investing in carp seed quality improvements in homestead aquaculture: lessons from Bangladesh. Aquaculture 453, 19–30. https://doi.org/10.1016/j.aquaculture.2015.11.027.

Kim, D.Y., Shinde, S.K., Kadam, A.A., Saratale, R.G., Saratale, G.D., Kumar, M., Syed, A., Bahkali, A.H., Ghodake, G.S., 2022. Advantage of species diversification to facilitate sustainable development of aquaculture sector. Biology 11 (3), 368. https://doi.org/10.3390/biology11030368.

Kruijssen, F., Adam, R., Choudhury, A., Danielsen, K., McDougall, C., Newton, J., Smits, E., Shelley, C.C., 2021. A Gendered Aquaculture Value Chain Analysis in Northwestern Bangladesh. WorldFish, Penang, Malaysia (Program Report: 2021-02).

Kumar, B.G., Datta, K.K., Joshi, P.K., Katiha, P.K., Suresh, R., Ravisankar, T., Ravindranath, K., Menon, M., 2008. Domestic fish marketing in India - changing structure, conduct, performance and policies. Agricult. Econom. Res. Rev. Agricult. Econom. Res. Assoc. (India) 21(Conference).

Kumar, G., Engle, C., Tucker, C., 2018. Factors driving aquaculture technology adoption. J. World Aquacult. Soc. 49 (3), 447–476. https://doi.org/10.1111/jwas.12514.

Little, D.C., Young, J.A., Zhang, W., Newton, R.W., Mamun, A.A., Murray, F.J., 2018. Sustainable intensification of aquaculture value chains between Asia and Europe: a framework for understanding impacts and challenges. Aquaculture 493, 338–354. https://doi.org/10.1016/j.aquaculture.2017.12.033.

Macfadyen, G., Nasr-Alla, A.M., Al-Kenawy, D., Fathi, M., Hebicha, H., Diab, A.H., Hussein, S.M., Abou-Zeid, R.M., El-Naggar, G., 2012. Value-chain analysis – an assessment methodology to estimate Egyptian aquaculture sector performance. Aquaculture 362–363, 18–27. https://doi.org/10.1016/j.aquaculture.2012.05.042.

MacRae, I.H., Chapman, G., Nabi, S.M.N., Dhar, G.C., 2002. A survey of health issues in carp/ macrobrachium culture in rice fields in Bangladesh. In: Arthur, J.R., Phillips, M.J., Subasinghe, R.P., Reantaso, M.B., MacRae, I.H. (Eds.), Primary Aquatic Animal Health Care in Rural, Small-Scale and Aquaculture Development. FAO Fisheries Technical Paper No, vol. 406, pp. 95–112.

Mahmud, A.I., Nazrul, W.I., 2013. Study on Fish Feed Formulation & Production in Mymensingh. LAP LAMBERT Academic Publishing, Bangladesh, p. 52.

Meah, M.M., Akther, K.R., 2021. Cost benefit analysis of fish farming at northern Chattogram, Bangladesh. Soc. Change 10, 163–271.

Msuya, F.E., Hurtado, A.Q., 2017. The role of women in seaweed aquaculture in the Western Indian Ocean and South-East Asia. Eur. J. Phycol. 52 (4), 482–494. https://doi.org/10.1080/09670262.2017.1357084.

Naylor, R.L., Hardy, R.W., Buschmann, A.H., Bush, S.R., Cao, L., Klinger, D.H., Little, D. C., Lubchenco, J., Shumway, S.E., Troell, M., 2021. A 20-year retrospective review of global aquaculture. Nature 591, 551–563. https://doi.org/10.1038/s41586-021-03308-6.

Paprocki, K., Cons, J., 2014. Life in a shrimp zone: aqua- and other cultures of Bangladesh's coastal landscape. J. Peasant Stud. 41 (6), 1109–1130. https://doi.org/10.1080/03066150.2014.937709.

Pham, N.T., Ng, R.K.S., Le, C.V., 2021. Transportation and marketing of aquaculture products in rural areas: case studies from Vietnam and Thailand. J. Rural. Stud. 82, 22–34.

Porter, M., 1985. Competitive Advantage: Creating and Sustaining Superior Performance. Free Press, New York.

Rahman, M.A., Monim, M., Mukta, M.A., Khatun, M., Roy, A.C., 2022. Shifting from paddy production for aquaculture: an economic study in a selected area of Bangladesh. Arch. Agricult. Environ. Sci. 7 (3), 415–424. https://doi.org/10.26832/24566632.2022.0703016.

Reardon, T., Chen, K.Z., Minten, B., Adriano, L., 2012. The Quiet Revolution in Staple Food Value Chains in Asia: Enter the Dragon, the Elephant, and the Tiger. Asian Development Bank and IFPRI.

Rico, A., Phu, T., Satapornvanit, K., Min, J., Shahabuddin, A.M., Henriksson, P.J.G., Van den Brink, P.J., 2013. Use of veterinary medicines, feed additives and probiotics in four major internationally traded aquaculture species farmed in Asia. Aquaculture 412–413, 231–243. https://doi.org/10.1016/j.aquaculture.2013.07.028.

Rohani, M.F., Islam, S.M.M., Hossain, M.K., Ferdous, Z., Siddik, M.A.B., Nuruzzaman, M., Padeniya, U., Brown, C., Shahjahan, M., 2022. Probiotics, prebiotics and synbiotics improved the functionality of aquafeed: upgrading growth, reproduction, immunity and disease resistance in fish. Fish Shellfish Immunol. 120, 569–589. https://doi.org/10.1016/j.fsi.2021.12.037.

Sabur, S.A., Palash, M.S., Lina, H.N., Haque, F.I., 2010. Profitability, marketing, and Price behavior of aquaculture fish fry and feed inputs in Bangladesh. J. World Aquacult. Soc. 41 (4), 519–532. https://doi.org/10.1111/j.1749-7345.2010.00392.x.

Sarker, M.A.A., Arshad, F.M., Alam, M.F., Mohamed, Z.A., Khan, M.A., 2016. Stochastic modeling of production risk and technical efficiency of Thai koi (*Anabas testudineus*) farming in northern Bangladesh. Aquac. Econ. Manag. 20 (2), 165–184. https://doi.org/10.1080/13657305. 2016.1156189.

Sarwer, R.H., 2021. Market Assessment and Business Analysis of Carp Feed in Northwest Bangladesh. A report submitted to WorldFish, House 335/A, Road 114, Gulshan-2, Dhaka-1212, Bangladesh.

Shikuku, K.M., Tran, N., Joffre, O.M., Islam, A.H.M.S., Barman, B.K., Ali, S., Rossignoli, C.M., 2021. Lock-ins to the dissemination of genetically improved fish seeds. Agric. Syst. 188, 103042. https://doi.org/10.1016/j.agsy.2020.103042.

Sohel, M.S.S.I., Ullah, M.H., 2012. Ecohydrology: a framework for overcoming the environmental impacts of shrimp aquaculture on the coastal zone of Bangladesh. Ocean Coast. Manag. 63, 67–78. https://doi.org/10.1016/j.ocecoaman.2012.03.014.

Swapan, M.S.H., Gavin, M., 2011. A desert in the delta: participatory assessment of changing livelihoods induced by commercial shrimp farming in Southwest Bangladesh. Ocean Coast. Manag. 54, 45–54. https://doi.org/10.1016/j.ocecoaman.2010.10.011.

Toufique, K., Gregory, R., 2008. Common waters and private lands: distributional impacts of floodplain aquaculture in Bangladesh. Food Policy 33 (6), 587–594. https://doi.org/10.1016/j.foodpol.2008.04.001.

Troell, M., Naylor, R.L., Metian, M., Beveridge, M., Tyedmers, P.H., Folke, C., Arrow, K. J., Barrett, S., Crépin, A., Ehrlich, P.R., Gren, A., Kautsky, N., Levin, S.A., Nyborg, K., Österblom, H., Polasky, S., Scheffer, M., Walker, B.H., Xepapadeas, T., Zeeuw, A., 2014. Does aquaculture add resilience to the global food system? PNAS 111 (37), 13257–13263. https://doi.org/10.1073/pnas.1404067111.

Van Houten, H.P., Schiffer, M.S., Hoang, L.D., 2019. Market access and transport costs: a study of fish marketing in the Mekong Delta. Aquac. Econ. Manag. 23 (3), 255–270.

Wahab, M.A., Nahid, S.A.A., Ahmed, N., Haque, M.M., Karim, M., 2012. Current status and prospects of farming the giant river prawn *Macrobrachium rosenbergii* (De man) in Bangladesh. Aquac. Res. 43 (7), 970–983. https://doi.org/10.1111/j.1365-2109.2012.03137.x.

World Economics, 2022. Bangladesh's social factors. Access 12December2022. https://www.worldeconomics.com/ESG/Social/Bangladesh.aspx.