DETERMINANTS AND OUTCOMES OF FORMULATED PELLETED FEED USE ACROSS DIVERSE AQUATIC FARMING SYSTEM IN BANGLADESH

by

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ABSTRACT

The study analyzes the drivers and outcomes of formulated and floating aquafeed adoption across a wide range of production systems including polyculture with different types of species combinations and aquaculture-agriculture integration. The study uses cross section data of 634 ponds from a fish and shrimp farmer survey conducted in 2020 from 7 southern districts of Bangladesh. The evidence shows a widespread adoption of formulated feed, but with a limited share of use. Although yield is higher among ponds with formulated feed use, it is only half of national yield capacity (5.2 t/ha) from pond culture, which creates an avenue to increase yield. The results of double-hurdle (DH) models show that species diversification with fish and prawns increases formulated feed use while specialization with only fish species spurs the use of floating pellets among formulated feed using ponds. Aqua-crop integration increases formulated feed use in extensive margin but reduces the intensity of its use. Surprisingly, larger ponds are less likely to apply floating feed than smaller ones. The matching estimator reveals that increased yield from formulated feed use is not sufficient to provide higher aquaculture income than traditional feed, due to associated higher feed costs. The uneven pattern of formulated feed use can be attributed to resource and knowledge constraints, as well as rational choices by pond owners. Having guidelines on appropriate and cost-effective combination of formulated and traditional feed based on species portfolio and stages of lifecycle, stocking density, and aqua-crop integration can contribute to nutrition security through accelerated aquaculture yield and income.

This thesis is dedicated to my parents, my spouse, and my brother.

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LIST OF ABBREVIATIONS

MT	Metric tons
kg	Kilogram
km	Kilometer
t/ha	Tons per hectare
USD/ha	United States Dollar per hectare
BDT	Bangladeshi Taka
BBS	Bangladesh Bureau of Statistics
SIS	Small and Indigenous Species
DH	Double hurdle
OLS	Ordinary Least Square
IMR	Inverse Mills Ratio
IV	Instrumental Variable
PSM	Propensity Score Matching
ATE	Average Treatment Effect
ATT	Average Treatment Effect on the Treated
SDG	Sustainable Development Goals

CHAPTER 1: INTRODUCTION

The rapid growth of aquaculture has been a major feature of the food production sector globally over the past 40 years. Formulated feeds have been a key technological change underlying accelerated growth of the sector. The use of formulated feed has facilitated intensification and higher yield per unit of other factors of production like land (Edwards et al., 2019; Naylor, Fang, & Fanzo, 2023; Tacon & Metian, 2015). Bangladesh has seen a similar trend of growing aquaculture supported by a dramatic shift in feeding form, including the increased use of both conventional and formulated feed, in semi-intensive to intensive production systems over the last three decades (Hernandez et al., 2018; Jahan et al., 2015; Mamun-Ur-Rashid et al., 2013).

Feed is of critical importance for aquaculture as it typically accounts for up to 80% of production costs and is a major factor in determining profitability and productivity (e.g., Ansari et al., 2021; Hasan, 2010). Previously, traditional feeds were prime source of nutrients for extensive and semi-subsistence small-scale fish farms, which can be of two categories: (a) naturally occurring feeds in the pond such as plankton and algae usually stimulated by application of manure or fertilizer to make them grow faster; (b) home-made feeds or grain mill byproducts such as rice bran, wheat bran, mustard oilcake, broken rice, maize, molasses etc. (Rola & Hasan, 2007; Zaher & Mazid, 1995).

Commercially formulated pelleted feeds have two variants: (a) sinking non-extruded or pressure-pelleted feed; (b) floating extruded pelleted feed. Formulated pelleted feed is more productive than traditional feed because pelleted feed is formulated to be nutritionally complete, supporting faster fish growth and yield with lower feed conversion ratio (FCR)—the ratio of the amount of feed applied to the pond and the amount of total harvest—than traditional feeds. Additionally, extrusion technology enhances the digestible energy content in floating feeds incorporating higher lipid concentrations. Floating pellets are more expensive but higher yielding due to less feed waste being more water stable compared to sinking pellets (Jobling, Gomes, & Dias, 2001). Sinking feeds may be more suitable for a few species like prawn and shrimp as bottom feeder species are unable to intake feed from water surface. Most fish species can accept extruded pellets which increase feed use efficiency and minimize feed waste greatly as farmers can adjust feed application based on observation (Craig et al., 2017).

Despite its importance in increasing farm productivity, use of formulated feeds is very uneven across different categories of farmers. This matters in Bangladesh, where aquaculture is a dynamic sector encompassing a broad array of production systems: from extensive with low feed to highly intensive with formulated feed, from monoculture to polyculture with varied degree of species diversification, and including aquaculture-crop integration (Ahmed, Wahab, & Thilsted, 2007; Alam et al., 2019; Belton, Haque, & Little, 2012). Previously, homestead ponds, belonging to almost every household in rural areas, were utilized for extensive aquaculture production (Belton, & Azad, 2012). Fish species get nutrients from natural feeds (algae and plankton) grown in homestead ponds. Several extension projects (Rand & Tarp, 2009; Thompson, Firoz Khan, & Sultana, 2006), expansion of aquafeed mills (Mamun-Ur-Rashid et al., 2013), and the development of aquafeed supply segment within aquaculture value chains (Ali et al., 2018) helped to drive the recent intensification in aquaculture seen in Bangladesh. This implies that fish production depends on external feeding. However, wide variability in the adoption of formulated feed is still prevalent and the reason behind this is not well understood and explored.

The global literature on aquaculture feed is dominated by two major strands: (1) technical literature on feed formulation (manufacturing processes or selection of ingredients to optimize the performance of feeds). (2) environmental impacts and environmental sustainability of feeds, including the controversial use of fish meal in aquaculture feeds. A subset of this literature examines the use of novel feed ingredients such as algae and insects as more sustainable replacements for fish meals (e.g., Ansari et al., 2021; Cottrell et al., 2020).

A small strand that received less attention than the previous two deals with the drivers and outcomes of feed adoption despite the critical role of pelleted feed in farm productivity and profitability. Within this we identify three sub-strands. The first sub-strand is composed of purely descriptive studies of the use of feed in different types of farms, describing how farmers started adopting pelleted feed in intensive and semi-intensive farming (e.g, De Silva & Hasan, 2007; Yuan, 2007).

The rest of the two sub-strands emerge with economic analysis of determinants and outcomes of adoption, respectively. Historically scholars assumed that only larger farms could afford to adopt formulated feeds. Some studies found that small farmers were unable to adopt feed due to capital constraints (Ike & Roseline, 2007). But there is evidence that increasingly, smaller farms also use formulated feed (Yi, Reardon, & Stringer, 2018) and greater revenue generation is possible from feed use (Petersen et al., 2011). As a result, there has been a growing interest in the literature concerning the other factors influencing feed adoption by smallholder farmers.

From the second sub-strand we observe that most studies employed fish farm surveys to identify associated factors in feed adoption. Findings revealed that participation in private aquafeed market was driven by the receipt of subsidized feed from government in Kenya (Amankwah, Quagrainie, & Preckel, 2016; Wafula et al., 2021). The price of formulated feed, age and education of farmer, access to extension services and credit, area under fishpond were other key determinants of adoption (Amankwah, Quagrainie, & Preckel, 2016; Amankwah & Quagrainie, 2019; Wafula et al., 2021). Training on feed formulation enabled fund-constraint farmers to produce their own aquafeed from locally available ingredients to supplement with purchased commercial feeds and thus accelerated the efficient use in Kenya and Ghana (Munguti et al., 2021; Ragasa, Osei-Mensah, & Amewu, 2022), and had positive income effects (Ragasa, Osei-Mensah, & Amewu, 2022). There is also evidence from India that farmers' familiarity of non-conventional ingredients (e.g., seaweeds, microalgae) positively influenced their perception of using aquafeed containing those ingredients along with some other factors: peer pressure, and benefit of aquafeed in term of aquaculture output (Brugere et al., 2021).

The latest small sub-strand of literature analyzes the outcomes of feed adoption by small farms (Amankwah & Quagrainie, 2019; Amankwah, Quagrainie, & Preckel, 2018; Obiero et al., 2019). Previous economic analysis documented the benefits of using formulated feed with higher fish growth in Philippines (Rola & Hasan, 2007) and as a replacement of small-sized fish in Vietnam (Grimm-Greenblatt et al., 2015). The limited use of improved feed below than the recommended level constrained the optimal output among aquaculture best management project (BMP) participants in Ghana (Amankwah & Quagrainie, 2019). They also found a positive impact of improved feed adoption on household welfare. Similar results were observed in the presence of government's aquaculture extension support program (ESP) where participants received aquafeed at subsidized rate (Amankwah, Quagrainie, & Preckel, 2018), and among aquaculture technology adopters in government subsidy program supported region (Obiero et al., 2019) in Kenya. However, they overlooked formulated feed use in their economic analysis. One experimental study of tilapia production assessed social welfare benefits in terms of net present value (NPV) of output with reduced production costs from such adoption (Ansah & Frimpong, 2015).

There have been some other studies exploring determinants and outcomes of improved management practices (IMP), training of farming systems as part of different aquaculture projects in Bangladesh (Kazal, Rahman, & Rayhan, 2020; Rahman, Kazal, & Rayhan, 2020; Rahman, Kazal, & Rayhan, 2020a). They focused on a single production system with prawn or crab. None of those studies dealt with adoption of formulated feed. Evidence from Indonesia showed that having prerequisite of productive assets, small farms adopted formulated feed in responsive breed (*P. vannamei.*) cultivation. The lack of such capacity constrained the adoption (Yi, Reardon, & Stringer, 2018).

From the march of the literature, we encountered several limitations.

First, within the literature we mainly identified papers in Africa, and farmers were participants of subsidy programs (Amankwah, Quagrainie, & Preckel, 2016; Amankwah, Quagrainie, & Preckel, 2018; Obiero et al., 2019), training programs (Ragasa, Osei-Mensah, & Amewu, 2022), other government lead projects (Amankwah & Quagrainie, 2019; Ogunremi & Oladele, 2012) or experimental projects (Ansah & Frimpong, 2015). As most aquaculture is not part of a project and isn't in Africa; there is value in exploring the determinants and outcomes of formulated feed adoption in places like Bangladesh.

Second, past studies typically focused on a single type of production system (e.g., growing one species of fish) (e.g., Ansah & Frimpong, 2015; Grimm-Greenblatt et al., 2015; Yi, Reardon, & Stringer, 2018). It is well known that aquaculture is a very diverse set of systems, especially in Bangladesh, with different types of polyculture beyond carp polyculture and fish-crop integration. There is huge scope of extension of previous studies beyond single breed or species, and single farming system encompassing agriculture-aquaculture integration, total owned and operated farm size, non-farm income.

Third, only one paper previously analyzed determinants and impact simultaneously (Amankwah & Quagrainie, 2019). The study was conducted among aquaculture BMP project participants with prime intention to make them adopt improved feed in Ghana. That is, the topic is not well covered in the literature.

Fourth, these papers often have small sample sizes and often have non-representative sampling methods (Ansah & Frimpong, 2015; Ogunremi & Oladele, 2012; Ragasa, Osei-Mensah, & Amewu, 2022). Therefore, there may be limits to the generalization of their findings.

Finally, very few studies from Asia, especially in Bangladesh, describe how poor farmers demand aquafeed, and those were based on single farming systems like carp polyculture (Mohan Dey et al., 2005). We found no studies on formulated feed adoption in Bangladesh under non-project conditions.

In sum, to the best of our knowledge, to date, no studies have explored formulated feed use and its impact considering a wide range of production systems including polyculture where fish species are combined with crustaceans, and fishponds can be non-integrated or integrated with agriculture or horticulture. To address this research gap, we explore formulated feed adoption in integrated systems and with a variety of species combination using a large representative sample. Those gaps lead to two research questions.

First, what factors influence the adoption and intensity of use of formulated feed? The term adoption represents the use of formulated feed in a randomly sampled parcel per farm household. That is, all outcome variables of interests are considered at plot/pond-level, not at farm-level because a farm household can have more than one active pond. We extend the above question to explore drivers correlated to floating pellet use among ponds that use formulated feed.

Having diversified farming systems with multiple different sets of combinations of species could be associated with two feed use outcomes. We hypothesize that ponds that specialized with fewer species or fewer combinations of different types of species, fish only for instance, are more likely to use formulated feeds. Similarly, the culture of only fish species without any crustaceans being combined with increases the use of floating pellets. The reason behind such hypothesis is that shrimp is cultured extensively with little feed use in Bangladesh and crustaceans being bottom dweller species are unable to intake floating feeds.

On the other hand, a wider range of species reared in the same pond with different feeding requirements can lead to the use of more formulated pellets. Different biological characteristics of aquatic species might necessitate the application of varieties of pelleted feeds.

Similarly, fish-crop integration can lead to two outcomes of pelleted feed use. On the one hand, we hypothesize a positive association of feed use with aquaculture-crop integration which might reduce capital constraints generating income or minimizing consumption expenditure as crop production can be destined for home consumption. On the other hand, integration may decrease feed use as farmed species are likely to get nutrients directly from runoff of applied fertilizer and manure in crops or indirectly from fertilizer-manure-induced growth of natural feeds in ponds.

Additionally, we also expect feed application to be correlated to the size of fishpond, and pond owner's size of landholdings, receipt of fisheries extension services and credit facilities. The above-mentioned factors may all affect the incentives and farmer's capacity to apply formulated feed in the sampled pond.

Second, from conventional wisdom, formulated pellets are usually associated with increased yield and profitability. However, tradeoffs may exist. To test the conventional wisdom, we ask: does the use of formulated feed increase both the aquaculture yield and income? We hypothesize that formulated feed generates significant positive impact on both aquaculture yield and income. On the one hand, by increasing yield formulated feed can increase profitability. On the other hand, the higher costs associated with purchasing formulated pellets may also offset the effect of higher yield and make the pond less profitable than traditional feed using ponds.

The results show that formulated feed application decision and the extent of use mostly vary by combination of species choice in polyculture settings. Species diversification –i.e., having prawns with fish species in the pond— is positively correlated with the use of formulated feed which includes both floating and sinking category and supports different feed requirements of fish and prawns. Conversely, specialization with only fish species in polyculture spurs both the participation decision and intensity of floating feed use among formulated feed users. This is also logical as floating feed is not suitable for bottom feeders.

We also find that feed adoption is positively correlated with aquaculture-crop integration, but integration reduces the intensity of formulated feed use. Extension services, and availability of aquafeed suppliers increase the probability of formulated feed adoption. The findings are almost similar for floating pellet users. Additionally, the receipt of credit increases the use of floating pellets, while household members' involvement in off-farm wage work reduces the extent of use. The size of landholdings has a positive correlation with feed use. Surprisingly, larger ponds are less likely to use floating pellets than smaller ones.

From matching estimator, we observe a positive impact of formulated pellet and floating pellet application on yield of aquaculture which is beneficial for macro-level food security. However, formulated feed doesn't generate significant positive impact on aquaculture income surpassing the increased feed cost. Therefore, future initiative should be directed to identify cost-effective combinations of formulated and traditional feed and conditions that can increase both yield and income using formulated feed.

Given the complexity of ponds with multiple species combinations, the uneven and partial adoption can be attributed to resource and knowledge constraints, as well as farmers' rational behavior. Farmers weigh the associated costs and benefits, making informed decisions about whether to use formulated feed in specific ponds.

The rest of the thesis is organized as follows. Chapter 2 presents materials and methods where data and descriptive statistics are followed by the estimation framework. The results and discussions are in chapter 3. Finally, the study concludes with policy implications in chapter 4.

CHAPTER 2: MATERIALS AND METHODS

2.1: Data and Descriptive Statistics

The study uses data from a fish and shrimp farm survey in 2020 in the seven major fish producing districts in Southern Bangladesh, which represent 43% of national aquaculture area and 24% of production. The surveyed districts accounted for 80% of production and 88% of aquaculture area in southern Bangladesh in 2021. The sample frame consisted of 13 sub-districts, selected by probability proportional to size of the population of aquaculture farms. Across 13 selected sub-districts, 721 households were selected for interview at random from the 2-3 wards (level below sub-district) with the most fish farms. Households may have several parcels dedicated to agriculture and/or aquaculture. One parcel was selected at random as a sample parcel if the household had more than one waterbody used for aquaculture. Detailed questions about aquaculture production were related to the sample parcel. All outcome variables of interests are from sample parcel. The data used for this study is a part of a large ‘stacked survey’ conducted with multiple segments and actors of aquaculture value chain in Bangladesh. Detailed description of data collection process can be found in data and methodology section of one of the previous studies, Ali et al. (2023).

We dropped observations that have issues from the data analysis. We dropped 12 observations due to their missing values for one of the key variables of interest – amount of feed used - for this analysis. Survey data were collected based on farmers’ memory of operating activities as they don’t keep written records. We identified a considerable number of outliers (75) for the combination of yield per ha, feed application rate per ha and FCR. Those observations were inconsistent with real scenario and existing literature. We dropped them as the inconsistent combinations of the three variables would jeopardize the results. After cleaning, we ended up with 634 households for final analysis.

Table 2.1: Distribution of aquafeed adoption and extent of use in sample parcel

Variables	N	Mean	CV
Distribution of household by participation (%)			
1. Formulated feed adoption	634	65	0.74
(i) Sinking feed adoption	634	46	1.08
(ii) Floating feed adoption	634	33	1.44
(a) Sinking feed adoption (conditional on formulated feed)	410	72	0.63
(b) Floating feed adoption (conditional on formulated feed)	410	51	0.99
2. Traditional homemade or grain mill by product feed	634	93	0.28
Intensity of adoption over total amount of feed use (%)			
1. Formulated feed use intensity	634	28	1.03
(i) Sinking feed use intensity	634	17	1.42
(ii) Floating feed use intensity	634	11	2
(a) Sinking feed use intensity (conditional on formulated feed)	410	26	0.98
(b) Floating feed use intensity (conditional on formulated feed)	410	17	1.49
2. Traditional homemade or grain mill by product feed use intensity	634	68	0.46
3. Ponds without any feed application	634	4	5.04

Note: CV denotes Coefficient of Variation, N indicates the number of observations.
Source: Author, based on 2020 fish and shrimp farm survey in Bangladesh

Fish farmers use a variety of feeds (ranging from 1 to 11) in cultured ponds; they prefer to combine one or two of the formulated feeds with several other traditional types. Most pond owners used formulated pellets, but these accounted for less than one third of their feed use. To wit, 65% of the sample ponds used pelleted feed which formed only 28% of their feed use. Jahan et al. (2015) reported similar findings. Although half of the ponds with pelleted feed applied floating pellet, intensity of use was quite low (17%). Traditional feeds (e.g., rice bran, broken rice, wheat bran, mustard oil cake) were used in almost every pond (93%), which constituted 68% of the feed use. A negligible number of ponds (4%) depended on naturally occurring plankton without any supplemental feed (Table 2.1). Explanatory variables used in this study were guided by farming systems, socio-economic characteristics of farmers, and previous relevant literature on technology adoption (Amankwah & Quagrainie, 2019; Kazal, Rahman, & Rayhan, 2020). Table 2.2 shows relevant plot level, household level, and community level variables.

Table 2.2: Descriptive statistics and measurement variables

Variables	Description	Mean N=634	Coefficient of variation
Farming systems (plot level)			
Integrated	If the sample parcel is integrated with rice or vegetables or fruits =1, otherwise 0	0.46	1.08
Fish only	If only fish species are cultivated in the sample parcel=1, otherwise 0	0.36	1.33
Fish prawn	If only fish and prawn are cultivated in the sample parcel=1, otherwise 0	0.24	1.77
Fish shrimp	If only fish and shrimp are cultivated in the sample parcel=1, otherwise 0	0.09	3.28
Fish Prawn shrimp	If only fish, shrimp, and prawn are cultivated in the sample parcel=1, otherwise 0	0.31	1.49
Tilapia	If the sample parcel produces tilapia=1, otherwise 0	0.70	0.66
Carp	If the sample parcel produces any carp species = 1, otherwise 0	0.94	0.25
Catfish	If the sample parcel produces any catfish species =1, otherwise 0	0.78	0.53
Household level variables			
Age (years)	Age of household head in years	49.16	0.26
Education (years)	Education of household head in years	6.37	0.7
Dependency ratio	Number of household members aged <15 and >65 years divided by those aged between 15 to 64 years old	0.54	0.97
Fish-farming experience (years)	Fish farming experience of household head in years	14.64	0.52
Off-farm paid job	If any member of household has off-farm paid job =1, otherwise 0	0.45	1.10

Table 2.2 (cont'd)

Off-farm paid job time (days)	Number of days household members involved annually in off-farm wage work	113	1.44
Self-employment	If any member of household has self-employment[1]=1, otherwise 0	0.78	0.53
Self-employed time (days)	Number of days household members involved annually in self-employment activities	312	0.71
Credit	If the household received any credit =1, otherwise 0	0.29	1.57
Extension fisheries	If the household received fisheries extension services=1, otherwise 0	0.04	5.05
Other plot level variables			
Area of sample parcel (ha)	Area of sample parcel in hectare	0.39	1.21
Active pond >1	If the household has >1 active ponds or ghers =1, otherwise 0	0.40	1.22
Owned area (ha)	Total owned area, including agriculture land and ponds, by farm household in hectare	0.68	1.38
Casual labor (person-days/ha)	Total casual labor used in fish farming annually in person-days per hectare	56.42	1.08
Distance home (km)	Distance of the sample parcel from home in Km	0.59	1.29
Distance road (km)	Distance of the sample parcel from nearest road in Km	0.32	1.18
Flood	If the sample parcel flooded during last 12 months=1, otherwise 0	0.39	1.25
Disease	If any fish suffered from any disease in the sample parcel during last 12 months=1, otherwise 0	0.30	1.52
Shannon Index (aqua)	Shannon diversity index for quantity of fish species produced in sample parcel	1.78	0.2
Outcome variables of interests (plot-level)			
Aqua yield (t/ha)	Total production from aquaculture in tons per hectare	2.08	1.22
Feed costs (USD/ha)[2]	Cost of feed and feed transportation in USD/ha	1031	1.87

[1] Self-employment represents farmers' involvement in any unpaid work other than aquaculture in sample parcel.
[2] 1 USD = 84 BDT (approximately) in 2020

Table 2.2 (cont'd)

Income from aquaculture (USD/ha)	Income= gross revenue – production costs	1504	1.57
Community (village) level variables (N=36)			
Village Feed suppliers	If the village has any fish feed supplier =1, otherwise 0	0.70	0.66
Village market	If the village has any market (permanent or temporary) =1, otherwise 0	0.94	0.25
Urban travel time (minutes)	Distance from urban area in monsoon season by the most common form of transport in minutes	26.4	0.49

Source: Author, based on 2020 fish and shrimp farm survey in Bangladesh

Among 634 households, almost half of the sample parcels (46%) were integrated with agriculture. Aquaculture and rice can be cultivated concurrently or alternatively on the same parcel. Pond dikes can be utilized for vegetables and fruit production. Roots of plants remain on the dikes; trellises support long vines of leafy or climbing vegetables e.g., cucumber, bottle gourd, ridge gourd, bitter gourd, snake gourd etc. crawling over water area. Farmers plant shrubs, bushes, and fruits bearing trees like mango, guava, lemon, papaya, banana, coconut, betel nut, jackfruit etc. on the elevated dike surrounding the pond. Aqua-rice and aqua-vegetables integration constituted 14% of the sampled parcels by each category and 18% of the parcels were devoted to aqua-rice-vegetables integration (Figure 2.1).

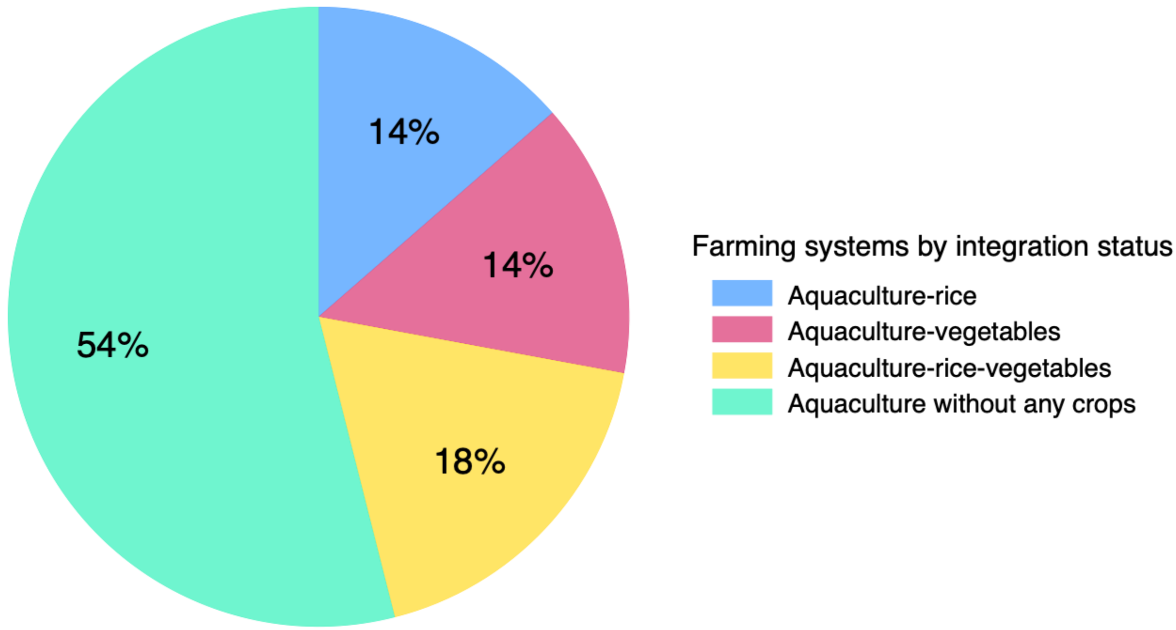

Figure 2.1: Distribution of sample parcels by aqua-crop integration status

Ponds are highly diversified in terms of numbers and types of aquatic species reared; species varied from 1 to 17 with a mean of 8 per pond. The Shannon index is a widely used diversification index developed by Shannon (1948), can capture the degree of aquatic species diversification in polyculture.

$$DI_{si} = -\sum_{i=1}^{n} P_i \ln P_i$$

Where, DI_{si} is the Shannon diversity index for fish species, P_i represents the proportion of production from a given fish species, and n is the total number of species cultured in the pond. The value can vary from $DI_{si} \geq 0$ where $DI_{si} = 0$ implies only one species reared in the pond. On the other hand, the higher the diversity of fish species, the greater the value of DI_{si} would be. This measurement captures both the richness of farmed species with the number of species in per unit of pond area and the proportional abundance of species in the parcel indicating the relative abundance of species in pond.

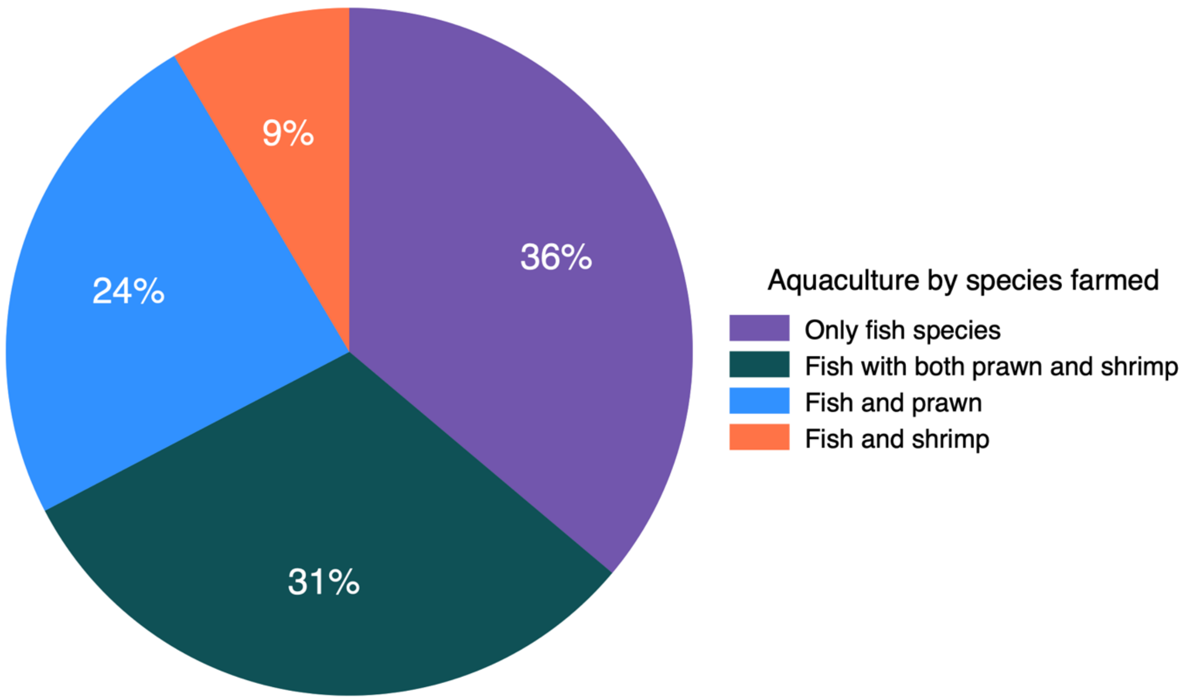

Figure 2.2: Distribution of sample parcels by aquaculture with species farmed

Figure 2.2 further illustrates this diversity of aquaculture operations. Among four major types of farming systems, 36% of the sample ponds produced only fish species while 24% combined fish with prawn, 9% fish with shrimp, and 31% had fish with both prawn and shrimp. The most common stacked species was carp: Rui, Catla, Mrigal, Silver Carp, Mirror Carp, Grass Carp, Common Carp, Bighead Carp etc. Jahan et al. (2015) also found carp to be the dominant species in commercial fishponds. Catfish (e.g., Magur, Shing), air-breathing fish (e.g., Koi, Shol), and Tilapia were also commonly reared fish species. Notably, more than half of the parcels had at least one crustacean species: prawn, shrimp, and mud crab. There were also some non-stocked fish species in 80% of the ponds, many of which were nutrient-rich small indigenous species (SIS) (e.g., Tengra, Puti, Mola) (Figure 2.3).

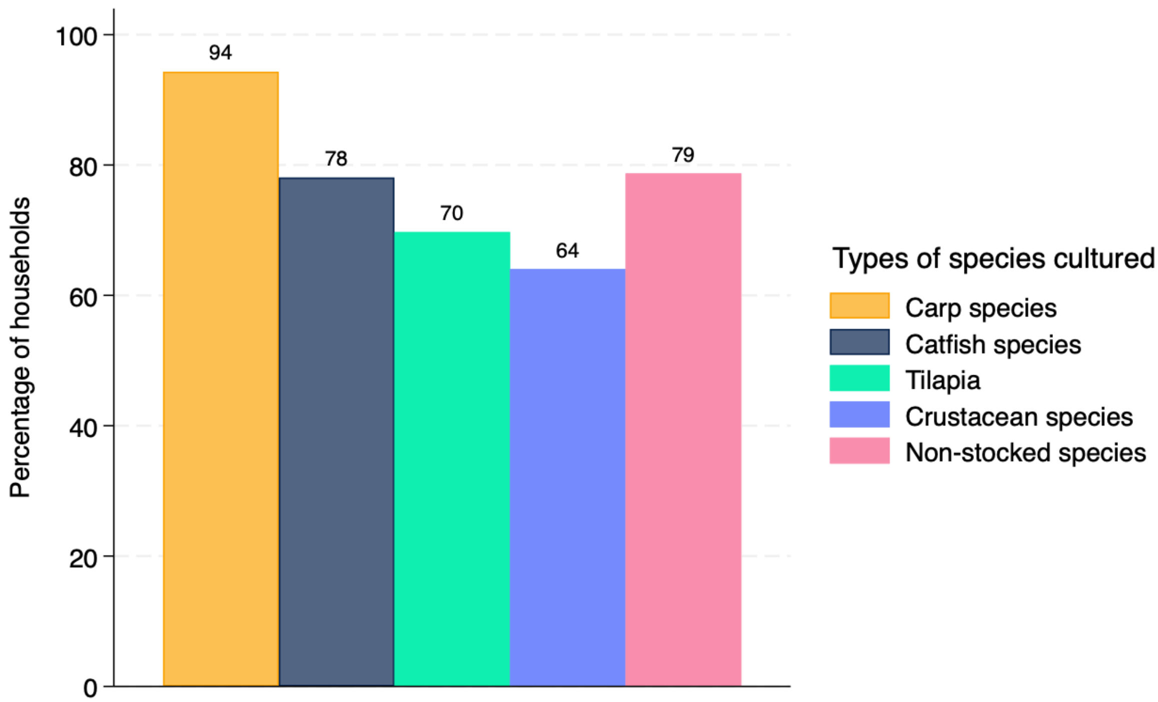

Figure 2.3: Distribution of sample parcels with types of species farmed

The average size of household (4.7) and dependency ratio (54%) were representative of the national household size and dependency ratio (51%) (BBS, 2022; BBS, 2020). On average, fish farmers attained 6.4 years of formal education, which is almost equal to the national average of 7 years (World Economics, 2022). Fish farming is an age-old profession in the surveyed region. Farmers were mostly middle aged with long-term experience in fish farming (14 years). Farming households were involved in varieties of rural self-employment activities other than aquaculture or non-farm wage work. Family members were engaged in self-employment activities along with fish farming in most of the households (78%). We categorize self-employment activities between involvement in agriculture and non-farm activities. About 62% of households had members self-employed in agriculture including both crop farming and livestock and poultry rearing; the latter was the most popular among farmers as a negligible percent of them were involved in crop farming. One-third of households had non-farm self-employment. Only in few (8%) farms, members were self-employed in fish harvest and trade related activities. Additionally, half of the households (45%) were involved in off-farm wage work. Of them, 14% worked as agricultural wage labor and 37% as non-farm labor. One-fifth of households were engaged in fish harvest, trade, and processing sectors as off-farm workers.

Only one-third of fish farmers received credit, and a negligible number of farms (4%) received fisheries extension services. Following the category of Bangladesh Bureau of Statistics (BBS), farm households are categorized into 4 types: marginal, small, medium, and large, based on their landholdings. Almost 80% of the farmers were in the marginal and small farmer category. Very few (19%) of them were medium-sized farmers whereas large farmers were rare (2%) in the survey area (Table 2.3).

Table 2.3: Types of farmers (according to BBS category)

	Number of farms	Percent of farms
Marginal farmers (owned area <=0.20 ha)	194	31
Small farmers (owned area >0.20 ha and <=1.00 ha)	305	48
Medium farmers (owned area >1.00 ha and <=3.00 ha)	122	19
Large farmers (owned area >3.00 ha)	13	2
Total	634	100

Source: Author, based on 2020 fish and shrimp farm survey in Bangladesh

Average aquaculture production was 2.08 t/ha, which is lower than the national aquaculture productivity (3.13 t/ha) from inland aquaculture, and it is the half of the national average yield from pond culture (5.2 t/ha) (DoF, 2022). This lower productivity can be explained by the prevalence of low intensity Shrimp farms – productivity is lower compared to fish species, but return is higher due to high price of final produce - in south-west Bangladesh. The highly intensive culture of fish species such as Pangasius (up to 40t/ha), Tilapia (up to 10 t/ha), and Koi (Belton & Azad, 2012) in other parts of the country accounts for this yield difference.

Bangladesh is a disaster-prone country and vulnerable to several natural calamities. Among others, floods are the most frequent with severe capacity to damage aquaculture. About 40% of the ponds were flooded during the last production cycle. It is difficult to prevent the escape of stocked species from inundated ponds during floods. This type of environmental shock negatively affects the overall production and aquaculture income. Availability of aquafeed suppliers in most villages might influence fish farmers adopting formulated feed through easy access. Notably, there were permanent or temporary markets in most of the villages.

We observe a significant difference in farming systems, and other factors by formulated feed use status. Aqua-crop integration (55%) was significantly higher among ponds that use formulated feeds. Feed users were more likely to practice fish-prawn farming system than non-users. Fish-shrimp and fish-prawn-shrimp systems were popular among traditional feed users. The carp was a significantly popularly reared species in ponds with formulated feed. The self-employment rate (81%) was also higher among formulated feed users; they were self-employed for more days (336 days/year) than those of traditional feed users (269 days/year). Ponds devoted to formulated feed (0.36 ha) were smaller than those managed by traditional feed only (0.45 ha). However, more casual labor was hired for formulated feed devoted pond than conventional feeding ponds. Shannon diversification index displays more species diversification in ponds with formulated feeds than ponds with traditional feeds (Table 2.4).

Table 2.4: Summary statistics by formulated feed and floating feed (conditional) use status

Variables	Formulated pelleted feed			Formulated floating pellet		
	Non-users N=224	Users N=410	Significance level[3]	Non-users N=203	Users N=207	Significance level
Farming systems (plot level)						
Integrated (0/1)	0.30	0.55	***	0.49	0.60	**
Fish only (0/1)	0.35	0.37	ns	0.31	0.43	***
Fish prawn (0/1)	0.11	0.31	***	0.32	0.31	ns
Fish shrimp (0/1)	0.13	0.06	***	0.09	0.02	***
Fish, prawn, and shrimp (0/1)	0.41	0.26	***	0.28	0.24	ns
Carp (0/1)	0.91	0.96	***	0.94	0.98	**
Catfish (0/1)	0.78	0.78	ns	0.74	0.82	**
Household level variables						
Age (years)	49.03	49.23	ns	50.67	47.83	**
Education (years)	6.07	6.53	ns	6.45	6.62	ns
Dependency ratio	0.50	0.56	ns	0.51	0.60	*
Fish-farming experience (years)	14.96	14.46	ns	15.01	13.92	ns
Off-farm paid job (0/1)	0.49	0.43	ns	0.43	0.43	ns
Off-farm paid job time (days)	127	105	*	103	106	ns
Self-employment (0/1)	0.71	0.81	***	0.82	0.81	ns
Self-employed time (days)	269	336	***	342	331	ns
Credit (0/1)	0.32	0.28	ns	0.22	0.33	***
Extension fisheries (0/1)	0.02	0.05	ns	0.04	0.05	ns
Other plot level variables						
Area of sample parcel (ha)	0.45	0.36	**	0.42	0.31	***
Active ponds >1 (0/1)	0.35	0.43	*	0.39	0.46	ns
Owned area (ha)	0.66	0.69	ns	0.68	0.70	ns
Casual labor (man-days/ha)	48	61	**	56.25	65.68	ns
Distance home (km)	0.63	0.56	ns	0.62	0.51	ns
Distance road (km)	0.28	0.34	*	0.30	0.37	*
Flood (0/1)	0.39	0.39	ns	0.29	0.49	***
Shannon Index (aqua)	1.74	1.81	**	1.78	1.83	Ns
Village level variables (N=36)						
Village Feed suppliers (0/1)	0.58	0.76	***	0.69	0.83	***

[3] Significance levels are from T-test, which represent the mean difference test.

Table 2.4 (cont'd)

Village market (0/1)	0.92	0.95	ns	0.91	0.99	***
Urban travel time (minutes)	24.15	27.62	***	24.66	30.53	***

Note: *** p<0.01, ** p<0.05, * p<0.1, ns = not significant
Source: Author, based on 2020 fish and shrimp farm survey in Bangladesh

We compare socio-demographic characteristics by floating pellet use status of ponds those use pelleted feed. A similar pattern is noticeable among floating pellets using ponds in aqua-crop integration and fish-shrimp farming systems. Additionally, ponds were specialized in polyculture with only fish species, devoid of any crustaceans (Table 2.4). Floating pellet users were comparatively younger than that of sinking pellet users with higher dependent members in households. We found more credit recipients among floating pellet users. The pond size also varies by floating pellets use status as we noticed among formulated feed users. To be specific, floating feed using ponds were prominently smaller and half of those (49%) were flooded during the last production year.

Table 2.5: Outcome variables of interests from sample parcel

	Formulated pelleted feed		Floating pellet	
	Users	Non-users	Users	Non-users
Aqua yield (t/ha)[4]	2.32***	1.62	2.85**	1.78
Feed costs (USD/ha)	1327***	491	1753***	893
Income from aquaculture (USD/ha)^{ns}	1498	1515	1478	1520
N	410	224	207	203

Note: *** p<0.01, ** p<0.05, * p<0.1, ns = no significant difference between adopters and non-adopters.
Source: Author, based on 2020 fish and shrimp farm survey in Bangladesh

The outcome variables of interests are presented in Table 2.5. We observe a significantly higher yield (2.32 t/ha) from formulated feed devoted ponds than that of traditional feed ponds. The pattern is similar for floating feed using ponds (2.85 t/ha) conditional on formulated feed use.

[4] *** p<0.01, ** p<0.05, * p<0.1 indicate significant difference between adopters and non-adopters

However, the yield is still far below the national average yield (5.2 t/ha) from pond culture. The widespread presence of shrimp farms in the study area is noticeable. Shrimp farming in an intensive culture system is a risky enterprise due to its susceptibility to disease. The high cost of shrimp seed and formulated shrimp feed make the intensive shrimp culture quite expensive. Additionally, the ignorance of appropriate feed management practice might be one reason driving this low yield. Farmers in that region lacked adequate contact with fisheries extension personnel. Application of formulated feed accounts for significantly higher feed expenditure in ponds.

2.2: Estimation Framework

2.2.1. Determinants of Feed Adoption in Sample Pond

Random utility theory is used as a framework, per which farmers adopt formulated pelleted feed in sample pond if the utility of fish yield or gross return from adoption surpasses the utility from non-adoption. That is, $U_{ma} > U_{mn}$ leads to formulated feed adoption where U_{ma} and U_{mn} represent the utility of yield or gross return from ponds with formulated feed and traditional feed, respectively. Similarly, $U_{fa} > U_{fn}$ drives floating pellet adoption among formulated feed using ponds where U_{fa} and U_{fn} denote utility from floating pellet and sinking pellet use, respectively. Discrete choice models (logit or probit) can explain the drivers behind the binary adoption of a technology. Adoption can be complex and beyond simple binary options in many cases. Instead of holistic application, farmers may adopt a part of technology or use the technology to a portion of their farm (Smale, Just, & Leathers, 1994). For instance, fish farmers in the surveyed regions used on average 4 different feeds (can vary up to 11). Most fish farmers (61%) combine formulated aquafeed with traditional ones. A negligible share of households (3.5%) depends on only formulated feed for pond culture. Some farmers (32%) completely depend on traditional aquafeed. In such cases, intensity of adoption comes to question which can be expressed as the ratio of amount of formulated feed to the total feed used in aquaculture. That is, adoption intensity of formulated feed,

$$T_{mi} = \frac{Q_{mi}}{Q_{ti}}$$

Where, Q_{mi} = amount of formulated aquafeed (kg/ha) and Q_{ti} = amount of total aquafeed (traditional + formulated) (kg/ha). Similarly, adoption intensity of floating pellet conditional on formulated feed use,

$$T_{fi} = \frac{Q_{fi}}{Q_{mi}}$$

Where Q_{fi}= amount of floating pellet (kg/ha).

For corner solution dependent variable, Tobit estimation could be an alternative to OLS (Ordinary Least Square) to model the binary adoption decision (Tobin, 1958). However, Tobit provides a single mechanism to determine both discrete adoption and intensity of adoption (Wooldridge, 2010). This gives same sign for the partial effects of both participation decision and extent of adoption (Wooldridge, 2009). In other words, relative effects are the same for two explanatory variables. That is,

$$\frac{\frac{\partial P(T_i > 0|x)}{\partial x_j}}{\frac{\partial P(T_i > 0|x)}{\partial x_h}} = \frac{\beta_j}{\beta_h} = \frac{\left(\frac{\partial E(T_i|x, T_i > 0)}{\partial x_j}\right)}{\left(\frac{\partial E(T_i|x, T_i > 0)}{\partial x_h}\right)}$$

Where the first ratio represents the relative effects on binary adoption and the last ratio depicts relative effects of the extent of adoption from Tobit estimation.

Double hurdle is more flexible over Tobit as it assumes that factors influencing the technology adoption decision to be different from factors affecting the intensity of technology adoption. We employed two double-hurdle (DH) models: one for formulated pelleted feed in general and another for floating pellet in particular as used in relevant studies before (e.g., Noltze, Schwarze, & Qaim, 2012; Reyes et al., 2012). The Cragg's DH model allows to capture two decisions: binary adoption with a probit model in the first stage and intensity of adoption with truncated normal regression model in the second stage (Cragg, 1971). The first hurdle identifies determinants of the discrete adoption decision as follows:

$$T_{i1}^{*} = \gamma x_{1i} + \epsilon_i$$

The latent variable, $T_{i1}^{*} = 1$ if T_i>0 vs $T_{i1}^{*} = 0$ if T_i=0 where T_i is the observed adoption intensity of expected technology. The second hurdle models determinants of intensity of adoption (T_{i2}^{*} takes the exact value of T_i given T_i>0). Notably, we denote the intensity of adoption of formulated aquafeed and floating feed by T_{mi}^{*} and T_{fi}^{*} respectively.

$$T_{i2}^{*} = \beta x_{2i} + \varepsilon_i$$

Where x_{1i} and x_{2i} represent potential factors (at the plot/pond, household, and village levels) that can explain the adoption as well as intensity of adoption of formulated pelleted feed in sample ponds. Subscript i denotes i-th household. γ and β are the intended parameters to be estimated. ϵ_i and ε_i are associated error terms which are assumed to be independently and normally distributed with mean zero and constant variance. That is, $\epsilon_i \sim N(0,1)$ and $\varepsilon_i \sim N(0, \sigma^2)$.

The log-likelihood function comes with the following formula for double hurdle estimation (e.g., Engel & Moffatt, 2014; Jones, 1989; Noltze, Schwarze, & Qaim, 2012):

$$LogL = \sum_{0} ln\left\{1 - \Phi(x_{1i}\gamma)\Phi\left(\frac{x_{2i}\beta}{\sigma}\right)\right\} + \sum_{+} ln\left\{\Phi(x_{1i}\gamma)\left(\frac{1}{\sigma}\right)\phi\left((T_{i2} - x_{2i}\beta)/\sigma\right)\right\}$$

Where, $\phi(.)$ denotes the standard probability density function and $\Phi(.)$ represents the standard cumulative distribution function. Both are assumed to be normally distributed.

Another alternative model suitable for limited dependent variable is Heckman's two-step sample selection model (Heckman, 1976). The model estimates a probit model in the first stage to address adoption decision. The second stage is designed to uncover responsible factors driving the intensity of adoption fitting an OLS equation of quantity adopted conditioned on the adoption decision being positive. Inverse mills ratio (IMR) can be calculated from first stage probit estimation generating predicted value of dependent variable. To address the selection bias of sample, drawn from the first stage conditional to $T_i > 0$, while estimating the second stage, the model uses IMR (λ) as an explanatory variable in OLS as follows:

$$T_{i2}^* = \beta x_i + \rho\lambda$$

The presence of sample-selection bias is identified by the significant value of the coefficient (ρ) of IMR which indicates suitability of Heckman's selection model over double hurdle proposed by Cragg. In this case, we obtained insignificant IMR from Heckman's two-step estimation.[5] Therefore, the double hurdle was appropriate for our sample data.

The significant value of chi-square from likelihood-ratio (LR) test indicated the rejection of the null hypothesis (H_0: the data and model specification are best fit by a Tobit). This justified the better suitability of double hurdle model for both corner solution dependent variables: formulated feed and floating feed use among formulated feed users over Tobit estimation. Moreover, the significant value of Wald $\mathcal{X}^2$ indicated the appropriateness of both double hurdle models for the sample data. From the first equation of DH model, we observe the probability of formulated feed or floating feed adoption.

$$P(T_i > 0|x_{1i}) = \Phi(x_{1i}\Upsilon)$$

Where the second hurdle is the truncated normal regression estimates the expected value of amount of intended feed adoption among adopters.

$$E(T_i|T_i > 0, x_{2i}) = \beta x_{2i} + \sigma\lambda(x_{2i}\beta/\sigma)$$

[5] Additionally, convergence was not achieved using Heckman's maximum likelihood estimation in STATA 18.

The inverse mills ratio (IMR), $\Upsilon\left(\frac{x_{2i}\beta}{\sigma}\right) = \phi(x_{2i}\beta/\sigma)/\Phi(x_{2i}\beta/\sigma)$

Following Burke (2009), we can obtain the overall expected value of adoption intensity given explanatory variables is as follows:

$$E(T_i|x_{1i}, x_{2i}) = \Phi(\Upsilon x_{1i})[x_{2i}\beta + \sigma\lambda(x_{2i}\beta/\sigma)]$$

We are interested in estimating three types of partial effects of explanatory variables on outcomes. First, the partial effect of a variable on pond-level binary adoption decision. For continuous outcome variable, $T_i > 0$ using the formula below we can get the partial effect:

$$\partial P(T_i > 0|x_1)/\partial x_j = \gamma_i \phi(x_1 \Upsilon)$$

Second, the partial effect of an explanatory variable given other explanatory variables (x_i) on the intensity of formulated feed or floating feed conditional on $T_i > 0$. This can be termed as conditional partial effect and calculated as follows:

$$\partial E(T_i|x_i, T_i > 0)/\partial x_j = \beta_j\{1 - \lambda\left(\frac{x_{2i}\beta}{\sigma}\right)[\left(\frac{x_{2i}\beta}{\sigma}\right) + \lambda\left(\frac{x_{2i}\beta}{\sigma}\right)]\}$$

Third, the overall partial effect of a variable x_j on the intensity of formulated feed or floating feed given other explanatory variables (x_i) and unconditional on the value of T_i. That is, the effect is not conditional on $T_i > 0$. In case of formulated feed adoption, this unconditional partial effect can be interpreted as the partial effect of a variable on the intensity of formulated feed application or floating feed application for any randomly selected pond regardless of whether they use formulated feed or not. This unconditional partial effect uses parameters from both probit model and truncated normal model while the conditional partial effect considers parameters only from the probit model. Therefore, unconditional partial effect of x_j on the intensity of formulated feed adoption unconditional on the amount of formulated feed[6] is given below:

$$\frac{\partial E(T_i|x_i)}{\partial x_j} = \Upsilon_j * \phi(x_1\Upsilon) * \left\{x_2\beta\ + \sigma\lambda\ \left(\frac{x_2\beta}{\sigma}\right)\right\} + \ \beta_j * \Phi(x_1\Upsilon) * \{1 - \lambda(x_{2i}\beta/\sigma)[\left(\frac{x_{2i}\beta}{\sigma}\right)$$

$$+ \lambda\left(\frac{x_{2i}\beta}{\sigma}\right)]\}$$

2.2.2. Effects of Formulated Feed Application in Sample Ponds

We are interested in assessing the outcome of formulated feed adoption and floating pellet adoption conditional on formulated feed use. Our outcome variables of interests are aquaculture yield (t/ha), feed expenditure (USD/ha), and aquaculture income (USD/ha). Assuming linear relationship between outcome variables and pond-level binary adoption, our model specification is as follows:

$$Y_i = \ \alpha X_i + \delta T_i + \ \upsilon_i$$

Where, Y_i denotes outcome variables of interests, T_i is the binary adoption indicator of formulated feed or floating pellet in sample pond, α and δ are interested parameters to be estimated, υ_i is error term. The estimation of δ can be inconsistent due to compromise of random assignment of aquafarmers between feed adopters and non-adopters. Several unobserved factors (e.g., risk taking behavior, financial constraints, management capacity) may drive farmers self-selection as they might decide to be adopters or non-adopters by themselves. The unobservable may be correlated to our dependent variables. The selection bias can be addressed through instrumental variable (IV) method which is not applicable in this case due to lack of strong valid IVs that fulfill basic two assumptions: IV is correlated with the adoption variable and IV is not correlated with the error

[6] We are aware about the fact that all expected values are conditional on the explanatory variables included in the model. The term "unconditional partial effect" used here is based on the restriction imposed on dependent variable to be strictly positive.

term. For non-experimental or quasi-experimental research design without baseline information, propensity score matching (PSM) can be used to estimate the effects of adoption on yield, feed expenditure, and income of aquaculture which has wide applicable evidence in outcome evaluation addressing selection bias (e.g., Mishra et al., 2016; Olabisi, 2017; Rahman & Majumder, 2021). The validity of results from this method depends on two assumptions. One, conditional independence which implies that adoption is not affected by unobserved factors. Second, the presence of sizeable common support which can address selection bias (e.g., Heckman et al., 1998; Dehejia & Wahba, 2002). Differences in several socio-demographic characteristics between the adopters and non-adopters would compromise randomization to be successful which can be tested by balancing property tests before and after matching (Maredia et al., 2018). Additionally, PSM can be estimated as a nonparametric method and doesn't require assumptions of the functional form to be linear between outcome and adoption or distributional pattern or exogeneity of covariates (Heckman & Vytlacil, 2007; Wooldridge, 2010). In the first stage of PSM, probability of adoption is estimated with logit or probit to get predicted propensity scores of adoptions T_i for each fish farming household based on covariates X_i. The propensity score ranges between 0 and 1. In the second step, each formulated or floating feed adopter was matched to a non-adopter within a common support region - allows every fish farmer equal opportunity of being adopter - based on similar propensity score. We tested the balancing property of covariates before estimating the average treatment effect for the treated (ATT). The formula of ATT is as follows:

$$ATT = E(Y_{1i} - Y_{0i} \,|X_i|) = E(Y_{1i} \mid Z_i = 1,\, X_i|) - E(Y_{0i} \mid Z_i = 0,\, X_i|)$$

All estimations were conducted using the statistical package STATA version 18.

CHAPTER 3: RESULTS AND DISCUSSION

3.1: Adoption of Formulated Feed in Sample Pond

Factors influencing both the probability and the intensity of adoption of commercially formulated pelleted aquafeed including both floating and sinking type are presented with double hurdle estimation in Table A-1 in Appendix. The selection model and truncated model indicate drivers of formulated feed adoption and the share of use, respectively. Table 3.1 represents associated three types of marginal effects: marginal effects on binary adoption, conditional marginal effects on the extent of formulated feed uses among adopters, and the unconditional marginal effects on formulated feed use. Marginal effects on binary adoption and intensity of adoption in sample pond by factors at different levels (e.g., plot/pond, household, and village levels, respectively) are displayed in Table A- 3 and A-4, respectively. We observe that the model turned out to be more efficient with the inclusion of household-level and village-level variables. However, the explanatory power of plot-level variables remains almost identical except for a small deviation in the only-fish farming system. Integrated aquaculture with vegetables in the same parcel increases the probability of formulated feed adoption by 11%. However, fish-rice integration has no significant effect on adoption decision although the coefficient is positive. Different species choice influences feed adoption differently. Polyculture where farmers combine fish species with prawn was positively correlated with the adoption decision as probability of adoption in sample pond increases by 21%. The probability of adoption reduces by 8% with an increase in pond size by 1ha as use of formulated feed in larger ponds is associated with high cost of large-scale investment. More educated farmers are more likely to adopt formulated feed in sample ponds. Receipt of fisheries extension services has a positive correlation with feed adoption decisions. The probability of adoption was 20% higher among farmers with extension contact.

Lack of technical know-how and knowledge of the benefits of technology can be the building-block in new technology adoption (Table 3.1).

Table 3.1: Marginal effects on formulated feed adoption in sample pond

Variables	(1) Marginal effects on binary adoption (Probit)	(2) Conditional Marginal Effects (Truncated)	(3) Unconditional marginal effects (Double hurdle)
Plot-level variables			
Fish-rice integration	0.013	**-0.141*** **	**-0.081*** **
	(0.053)	(0.029)	(0.027)
Fish-vegetable/fruit integration	**0.113** **	**0.057* **	**0.082*** **
	(0.043)	(0.030)	(0.024)
Fish only	0.080	0.074	**0.079** **
	(0.073)	(0.053)	(0.039)
Fish prawn	**0.207*** **	0.024	**0.104** **
	(0.074)	(0.050)	(0.050)
Fish Shrimp	-0.013	0.017	0.006
	(0.079)	(0.046)	(0.046)
Casual labor (man-days/ha)	0.0001	-0.00001	0.00003
	(0.0001)	(0.00004)	(0.00004)
Area of sample parcel (ha)	**-0.078* **	-0.057	**-0.067** **
	(0.047)	(0.043)	(0.031)
Distance home (km)	-0.028	0.004	-0.008
	(0.027)	(0.023)	(0.019)
Distance road (km)	0.087	0.023	0.049
	(0.057)	(0.033)	(0.034)
Household-level variables			
Dependency ratio	0.028	0.021	0.025*
	(0.039)	(0.024)	(0.014)
Age (years)	0.002	-0.0004	0.0005
	(0.002)	(0.001)	(0.001)
Education (years)	**0.007** **	0.001	0.003
	(0.003)	(0.003)	(0.002)
Fish-farming experience (years)	-0.0007	-0.0004	-0.001
	(0.003)	(0.002)	(0.002)
Off-farm paid (0/1)	-0.016	-0.012	-0.014
	(0.041)	(0.027)	(0.021)
Off-farm self-activity (days)	0.0002*	-0.00008	0.00002
	(0.0001)	(0.00005)	(0.0001)

Table 3.1 (cont'd)

Owned operated area (ha)	0.031	**0.038*****	**0.037****
	(0.022)	(0.012)	(0.011)
Credit (0/1)	0.018	0.021	0.021
	(0.054)	(0.028)	(0.027)
Extension fisheries (0/1)	**0.204*****	0.044	**0.124*****
	(0.048)	(0.044)	(0.043)
Village-level variables			
Village feed suppliers (0/1)	**0.141*****	-0.085**	0.001
	(0.055)	(0.038)	(0.027)
Permanent village market (0/1)	0.086	-0.046	0.004
	(0.070)	(0.047)	(0.035)
Urban travel time (minutes)	0.003	0.002	0.002*
	(0.003)	(0.001)	(0.001)
Observations	634	410	634

Standard errors are clustered at village level in parentheses (*** p<0.01, ** p<0.05, * p<0.1)
Source: Author, based on 2020 fish and shrimp farm survey in Bangladesh

Extension officers facilitate dissemination of relevant information, sometimes through demonstration, among farmers and spur the adoption rate. This goes in line with the findings of Amankwah & Quagrainie (2019). That is, easy access to fisheries extension services in aquaculture-centric rural areas is important to elevate the adoption of formulated feed. Similarly, availability of aquafeed suppliers in the village is positively correlated to farmers' adoption probability by 14%.

Once feed is adopted, the same factors are not discerning the extent of feed use in sample pond. The integrated fish-rice system reduces the intensity of formulated feed applied in sample parcel by 0.14 unit. Applied manures and fertilizers in crop cultivation in integrated parcels may have two-fold benefits. First, the run-offs enhance microbial growth, fertilize bottom soil of pond, generate plankton bloom which can be a great source of feed in fish polyculture. Thus, integration can have a positive spillover effect on aquaculture and curtail the necessity of higher use of formulated feed. Second, it can be used as feed directly to many bottom dwelling fish species (e.g.

Prawn, Shrimp, Mrigal, Mirror carp) and mid-level feeders (e.g. Rohu). Previous evidence of better resource utilization under rice-fish integration (Ahmed & Garnett, 2011) supports this finding. Surprisingly, the fish vegetable integration predicts higher level of formulated feed use. This is likely due to direct or indirect income effects. Vegetables production can directly generate income from sales or indirectly release funds from consumption expenditure if vegetables are destined for home consumption. In both cases, fish-vegetable integration can influence more investment in formulated aquafeed. Polyculture with different fish species except any crustaceans had a correlation with the share of formulated feed application in ponds and this system increases the share of use by 0.07.

Adoption intensity was positively correlated with the size of land owned by farmer. That is, the higher the area including aquacultural and agricultural parcels owned by the household, the greater the share of formulated feed used in aquaculture.[7]

3.2: Robustness Check of Formulated Feed Adoption

We also analyze data using a subset of farm households with only one pond as a robustness check, presented in Table A-5, to see whether the farm is an adopter or non-adopter of formulated feed. In this case, the decision farmers are making would be equivalent to farm-level decision. The results are similar except for a few variations in significance level of unconditional marginal effects, displayed in model (3), of fish-rice integration, only fish species, and fish-prawn farming systems. Comparing findings from Table A-5 and A-6, we observe almost identical results from one-pond farms to that of farms having more than one pond.

[7] Unconditional marginal effects on formulated feed use in aquaculture are presented in Table 3.1(model 3). Tobit estimation is presented in Table A-2 for robustness check of unconditional marginal effects.

3.3: Adoption of Floating Feed Conditional on Formulated Feed Use in Sample Pond

As before, we document marginal effects on binary adoption (Table A-9) and share of use (Table A-10) of floating pellets in sample pond by factors at plot/pond, household, and village levels, respectively. We observe almost identical explanatory power of plot-level variables, with a negligible deviation, after household and village levels variables being added in model 2 and 3, respectively. However, such inclusions improve the efficiency of the model. Marginal effects on floating pellets use in ponds with formulated feeds are presented in Table 3.2.[8]

Table 3.2: Marginal effects on floating feed adoption in ponds with formulated feed

Variables	(1) Marginal effects on binary adoption (Probit)	(2) Conditional marginal effects (Truncated model)	(4) Unconditional marginal effects (Double hurdle)
Plot-level variables			
Integrated	**0.107***	**-0.075***	-0.010
	(0.064)	(0.042)	(0.026)
Fish only	**0.261*****	**0.180*****	**0.156*****
	(0.092)	(0.052)	(0.044)
Fish prawn	0.047	0.007	0.015
	(0.116)	(0.056)	(0.047)
Fish shrimp	-0.074	0.155	0.048
	(0.133)	(0.117)	(0.066)
Catfish	**0.155***	-0.004	0.038
	(0.082)	(0.057)	(0.040)
Casual labor (man-days/ha)	0.001	0.0001	0.0002
	(0.001)	(0.0003)	(0.0002)
Area of sample parcel (ha)	-0.204*	-0.013	-0.058
	(0.103)	(0.084)	(0.051)
Distance home (km)	-0.068*	-0.068	-0.051**
	(0.039)	(0.042)	(0.024)

[8] The coefficient estimation of double hurdle model is in Table A-7 and Tobit estimation is in Table A-8 in appendix.

Table 3.2 (cont'd)

Distance road (km)	**0.203****	-0.009	0.047
	(0.073)	(0.059)	(0.031)
Flood (0/1)	**0.155*****	-0.024	0.027
	(0.069)	(0.032)	(0.017)
Household-level variables			
Dependency ratio	0.080	0.044	**0.043***
	(0.063)	(0.027)	(0.022)
Age (years)	**-0.005****	-0.0002	-0.001
	(0.002)	(0.002)	(0.001)
Education (years)	0.001	**0.006****	**0.003***
	(0.006)	(0.003)	(0.002)
Fish-farming experience (years)	-0.004	0.00002	-0.001
	(0.005)	(0.002)	(0.001)
Off-farm paid (0/1)	0.019	**-0.079****	-0.036
	(0.057)	(0.033)	(0.024)
Off-farm self-activity (days)	-0.0002	-0.00014*	-0.0001**
	(0.0002)	(0.0001)	(0.0001)
Credit (0/1)	**0.174*****	0.035	**0.062*****
	(0.065)	(0.035)	(0.022)
Extension fisheries (0/1)	0.123	0.088	0.072
	(0.135)	(0.105)	(0.054)
Owned operated area (ha)	**0.065****	**0.024****	**0.028****
	(0.027)	(0.011)	(0.008)
Village-level variables			
Village feed suppliers (0/1)	0.144	-0.030	0.022
	(0.088)	(0.040)	(0.031)
Village market	**0.358*****	-0.380***	-0.038
	(0.079)	(0.088)	(0.027)
Urban travel time (minutes)	0.007**	0.005***	0.004***
	(0.002)	(0.001)	(0.001)
Observations	410	207	410

Note: Standard errors are clustered at village level in parentheses. ***p<0.01, **p<0.05, *p<0.1
Source: Author, based on 2020 fish and shrimp farm survey in Bangladesh

From the probit regression we observe that aquaculture-agriculture integration is positively correlated with the probability of floating feed adoption among formulated feed users by 11% as integration may increase investment in floating feed through income effect. The probability of adoption increases by 26% if the pond is specialized in fish polyculture without any crustaceans. The size of sample parcel had a negative correlation with adoption of floating feed. This result supports the findings presented in Table 3.1.

The distance of sample parcel from the nearest road has a positive correlation with floating feed use. This is surprising, and due to limitations of data we are unable to explain the mechanism behind this result. The occurrence of flood in the previous production cycle increases adoption probability by 16%. Farmers may use floating feed as an adaptation strategy. It is almost impossible to prevent the escape of fish from inundated ponds. Using floating feed, farmers might want to minimize the loss with faster growth of the reminder fish in the time left. However, due to lack of detailed information it is not possible to identify if farmers use floating pellets before or after flood.

We identify a negative correlation between the age of farmers and floating feed adoption. This implies that one year increase in age of farmers reduces the likelihood of floating feed adoption by 0.5%. Although the degree of reduced adoption is quite small, it can be explained as old farmers being risk averse are reluctant to try expensive technology.

Lack of credit facility is assumed to be the prime constraint for any technology adoption among small farmers in developing countries. Credit recipient farmers are more likely to adopt floating feed, which is a more expensive category, as credit availability fosters the probability of adoption by 17%. Previous studies also identified a higher likelihood of adoption of improved aquaculture technology among farmers with access to formal credit (Amankwah & Quagrainie, 2019; Kazal, Rahman, & Rayhan, 2020) which can minimize the associated capital constraints providing more flexibility to invest in expensive technology like floating feed. The presence of permanent or temporary markets in the village intensifies the adoption probability by 36%.

From marginal effect estimation of the truncated regression (Table 3.2, model 2) we can see that most of the factors are unable to explain the drivers of intensity of use in ponds where floating pellets are already applied. Although integrated ponds escalate the probability of adoption, integration shows a negative correlation with the share of floating feed used in ponds with formulated feed. The findings support what we have observed for aquaculture-rice integration in case of formulated feed use. Conversely, cultivation of fish species, without any crustaceans being combined with, in polyculture increases the share of floating feed use by 0.18%. As we have mentioned earlier, many crustaceans are bottom dwellers and unable to intake floating pellets.
The higher the years of education attained by farmers, the greater the share of floating feed use. Similarly, farm size had a positive correlation with feed use which implies that the share of floating pellet application is increased by 0.024 with an increase in farmer's owned and operated area by 1 ha. Household members' involvement in off-farm paid work reduces the share of floating feed application by 0.08 unit. Off-farm paid job restricts members' availability of being engaged in fish farming. It is highly likely that if someone is unable to devote enough time to day-to-day operations in intensive aquaculture, they would be less likely to invest in expensive technology like floating feed.

3.4: Robustness Check of Floating Pellets Adoption

Analyzing a subset of farms having only one pond we observe a little variation in the significance level of marginal effects of several factors: integration, area of sample parcel, age of farmers, off-farm paid work by family members, owned and operated area as farm size on adoption decision. Similar variations are noticeable in both conditional and unconditional marginal effects of floating pellet application in formulated feed using ponds (Table A-11). Table-12 represents marginal effects on the use of floating pellets by single-pond farms including a few households with more ponds. We find almost identical results between single-pond farms and farms having more than one pond are displayed in Table A-11 and Table A-12, respectively.

3.5: Impact of Formulated and Floating Feed Adoption in Sample Pond

The visual representation of common support with distribution of propensity scores for adopters and non-adopters are presented in Appendix (Figure A-1, A-3). The balance plots of propensity scores before and after matching are shown in Figure A-2 and A-4, indicate a balance between covariates after matching. Additionally, we test each covariate to scrutinize their balancing property before and after matching for formulated feed and floating pellets adopters (Tables A-13, A-14). Results indicate that standardized differences and variance ratios are approximated to 0 and 1, respectively, for matched sample, except for a negligible deviation in formulated feed adopters. This implies that balancing property is satisfied capturing the balance between treatment and control.

Table 3.3 presents the average treatment effects (ATE) and the average treatment effects on the treated (ATT) using probit estimation of PSM. We observe the effects of formulated feed adoption on all fish farmers, where ATT represents the effect of formulated feed use on adopters considering their counterfactuals. The results indicate that both yield of aquaculture and feed expenditure increase by on average 0.38 t/ha and 605 USD/ha if all farmers use formulated aquafeed in sample pond compared to if none of them use it. However, the ATT on yield from formulated feed use is positive while costs of feed are still significantly higher. Formulated feed would increase the feed expenditure by 580 USD/ha considering the counterfactual which is the group of adopters if they haven't adopted formulated feed.

We observe similar findings for floating pellet use on aquaculture yield and feed expenditure. Results reveal that yield and feed costs increase significantly by 0.62t/ha and 506 USD/ha, respectively if all formulated feed using ponds use floating pellet compared to none of them using this category. ATTs were also positive and significant at 5% level indicating that use of floating pellets can lead to a significant increase in both yield (by 0.77 t/ha) and feed expenditure (by 559 USD/ha).

Surprisingly, adoption has no significant effect on aquaculture income. That is, feed adoption doesn't generate higher income among adopters although we observe that yield can be increased by adoption. This is because of the associated high purchasing and transportation costs of formulated pelleted feed which offset the increased yield.

Table 3.3: Average effects of formulated feed and floating feed use in sample pond

Outcome variables of interests	PSM (probit)			
	Use of formulated pelleted feed		Use of formulated floating pellet	
	ATE	ATT	ATE	ATT
Aquaculture yield (t/ha)	**0.380**** (0.189)	0.136 (0.206)	**0.616***** (0.206)	**0.768**** (0.342)
Feed expenditure including transaction cost (USD/ha)	**605***** (138.36)	**580***** (132.02)	**506***** (170.10)	**559**** (265.15)
Income from aquaculture (USD/ha)	-54 (205.11)	-149 (213.55)	-182 (249.97)	40 (335.21)

Note: Robust standard errors are in parentheses (*** p<0.01, ** p<0.05, * p<0.1)
Source: Author, based on 2020 fish and shrimp farm survey in Bangladesh

We disaggregate the analysis over subsets of farms based on four aqua-farming systems to see the how farmers are doing in terms of yield, feed expenditure, and income from aquaculture based on their choice of species combinations in sample pond. Yield ranges from 0.2 t/ha to 7 t/ha for all farming systems except for ponds with only-fish species where farmers harvested up to 36 t/ha of fish (Figure A-5). Feed expenditure and income from aquaculture follow almost identical distribution for fish-prawn and fish-prawn-shrimp farming systems (Figure A-6 and A-7). Yield, feed expenditure, and income are higher in ponds having polyculture with several fish species devoid of any crustaceans than that of other three categories of the system. Conversely, ponds having fish species combined with shrimp spend least on feed costs among all systems. Both Yield and income are also lower in this farming system than others.[9]

[9] Financial analysis of aquaculture (pond polyculture) is presented in Table A-15.

CHAPTER 4: CONCLUSION AND POLICY IMPLICATIONS

Aquaculture can be a great source of animal protein at affordable prices through expanded production. Formulated feed is the most important technological innovation associated with increasing aquaculture productivity in Bangladesh and globally. This paper's contribution is to identify contributing factors of formulated feed adoption and to quantify the outcomes of adoption, under non-project condition in Bangladesh, across ponds with varying characteristics like polyculture with fish and crustaceans, and aquaculture-agriculture integration. The present study follows on but extends previous research by Mohan Dey et al. (2005), Yi, Reardon, & Stringer (2018) as we've controlled for aqua-crop integration, several farming systems beyond single species/breeds, farm size, and non-farm employment. Secondly, the surveyed regions contribute to only one-fourth of national output, encompassing almost half of the aquaculture area, where fish farming is the primary profession to considerable share of households. Therefore, findings from this empirical study can inform efforts to increase aquaculture productivity resulting greater contribution to national aquaculture production, farmers' income, and nutrition security debate in Bangladesh.

From the fish and shrimp survey in 2020 in the seven major fish producing districts of southern Bangladesh, and using double-hurdle models and PSM estimators, the study identifies the following results:

1. The formulated feed adoption is uneven and partial in the survey area: the adoption is widespread, but with a limited extent of use compared to traditional feeding. Although the adoption generates higher yield, it is still below the national average yield from pond culture. There is huge potential to increase yield following the appropriate feed

management practice; that can greatly increase the contribution from southern regions to national aquaculture output.

2. Feed adoption mostly varies by combination of species and aquaculture-crop integration status of parcel. Adoption of formulated feed is higher in species diversified (prawns with fish) ponds but the extent of use is higher in polyculture specialized with only fish species. Floating feed, being not suitable for bottom feeders, adoption is higher in only fish species farming system.
3. We observe the duality of aqua-crop integration status on adoption decision and extent of feed use. On the one hand, more investment in feed is possible with income from the sale of crops and vegetables grown in integrated pond. Consumption of crops can reduce household food expenditure too. On the other hand, fish can get nutrients directly from those inputs or indirectly from microbial growth, fertilized bottom soil of pond, plankton bloom which can be a great source of feed in polyculture. Such positive spillover effects might reduce the necessity of higher amount of formulated feed providing better resource utilization.
4. Extension contacts accelerate the adoption of formulated feed while the receipt of credit with a positive correlation increases floating pellet adoption minimizing fund constraints. Associated high investment cost held back farmers from using floating feed in larger ponds. The greater the landholdings, the higher the share of both formulated feed and floating pellet application in formulated feed using pond.
5. Adoption of formulated feed increases yield from aquaculture but doesn't generate significant positive impact on aquaculture income surpassing the increased feed cost.

The concern of sufficient micronutrients intake along with energy from staple grain is echoed in targets 2.2 and 2.3 of sustainable development goals (SDGs). Bangladesh aims to eradicate all forms of malnutrition by 2030. The focus is on doubling the productivity and income of small-scale food producers underscoring several sections including family farmers and fishers (United Nations Bangladesh, 2024). Sustained growth and development of aquaculture can have manifold effects. It can ensure increased production of nutrient-rich aquatic organisms, access to nutritious food at reasonable prices to non-fish-farming consumers, dietary diversity to fish-farmers through markets access with higher income accrued from aquaculture.

Based on this situation and findings of this study, there are two major policy implications:

1. Given a complex set of farming systems existing with multiple species combinations, the uneven and partial adoption can be explained by the resource and knowledge constraints, and farmers rational behavior because they understand the associated cost and benefits of using formulated feed. Access to credit for fish farmers on easy terms and dissemination of knowledge about nutrition contents of different types of feeds, proper trainings to farmers on making formulated feed at home with locally available ingredients, improvement of efficiency of feed mills (upgradation of equipment to ensure less electricity use) etc. can act as catalysts in this issue.
2. Increased yield from formulated feed adoption is beneficial in achieving food security from the macro-level point of view. However, if it fails to generate a positive impact on income, it would not be beneficial for farmers. Future initiative should be taken to identify what combinations of formulated and traditional feed considering types of species portfolio in polyculture, their stages of lifecycle, stocking level and density, and level of aquaculture-agriculture integration are most cost-effective or under which conditions formulated feed

can increase both yield and income. Government and non-government institutions can step forward with a collaborative effort with appropriate guidelines.

Despite the above contribution and policy implication, the study has some limitations. We consider only sample parcel to define adopters or non-adopters of formulated feed due to data constraints. However, a farm household may have more than one pond at a time, and we didn’t have detailed information about feed adoption on parcels other than sample pond. Additionally, we are unable to understand the coping strategy of flood affected ponds: whether they apply floating feed before or after flood. Unpacking the heterogeneity of the impacts of feed adoption over different farming systems would be a great avenue for future research.

BIBLIOGRAPHY

Ahmed, N. and Garnett, S. T. 2011. Integrated rice-fish farming in Bangladesh: meeting the challenges of food security. *Food Security,* 3, 81-92.

Ahmed, N., Wahab, M. A. and Thilsted, S. H. (2007). Integrated aquaculture–agriculture systems in Bangladesh: potential for sustainable livelihoods and nutritional security of the rural poor. *Aquacult. Asia* 12, 14–22.

Alam, M. M., Haque, M. M., Aziz, M. S. B. and Mondol, M. M. R. (2019). Development of pangasius–carp polyculture in Bangladesh: Understanding farm characteristics by, and association between, socio-economic and biological variables. *Aquaculture,* 505, 431-440.

Ali, H., Rahman, M. M., Murshed-e-Jahan, K. and Dhar, G. C. (2018). Production economics of striped catfish (*Pangasianodon hypophthalmus,* Sauvage, 1878) farming under polyculture system in Bangladesh. *Aquaculture,* 491, 381-390.

Amankwah, A. and Quagrainie, K. K. (2019). Aquaculture feed technology adoption and smallholder household welfare in Ghana. *Journal of the World Aquaculture Society*, 50(4), 827-841.

Amankwah, A., Quagrainie, K. K. and Preckel, P. V. (2018). Impact of aquaculture feed technology on fish income and poverty in Kenya. *Aquaculture Economics & Management*, 22(4), 410-430.

Amankwah, A., Quagrainie, K. K. and Preckel, P. V. (2016). Demand for improved fish feed in the presence of a subsidy: a double hurdle application in Kenya. *Agricultural Economics*, 47(6), 633–643.

Ansah, Y. B. and Frimpong, E. A. (2015). Impact of the adoption of BMPs on social welfare: A case study of commercial floating feeds for pond culture of tilapia in Ghana. *Cogent Food & Agriculture*, 1(1), 1048579.

Ansari, F. A., Guldhe, A., Gupta, S. K., Rawat, I. and Bux, F. (2021). Improving the feasibility of aquaculture feed by using microalgae. *Environmental Science and Pollution Research*, 28(32), 43234-43257.

BBS, (2022). Household Income and Expenditure Survey (HIES) 2022. Bangladesh Bureau of Statistics (BBS), Dhaka

BBS, (2020). Report on Bangladesh sample vital statistics 2020. Bangladesh Bureau of Statistics (BBS), Dhaka

Belton, B. and Azad, A. (2012). The characteristics and status of pond aquaculture in Bangladesh. *Aquaculture,* 358, 196-204.

Belton, B., Haque, M. M. and Little, D. C. (2012). Does size matter? Reassessing the relationship between aquaculture and poverty in Bangladesh. *Journal of Development Studies,* 48(7), 904-922.

Brugere, C., Padmakumar, K. P., Leschen, W. and Tocher, D. R. (2021). What influences the intention to adopt aquaculture innovations? Concepts and empirical assessment of fish farmers' perceptions and beliefs about aquafeed containing non-conventional ingredients. *Aquaculture Economics & Management*, 25(3), 339-366.

Burke, W. J. (2009). Fitting and interpreting Cragg's tobit alternative using Stata. *The Stata Journal,* 9(4), 584-592.

Cottrell, R. S., Blanchard, J. L., Halpern, B. S., Metian, M. and Froehlich, H. E. (2020). Global adoption of novel aquaculture feeds could substantially reduce forage fish demand by 2030. *Nature Food*, 1(5), 301-308.

Cragg, J. G. (1971). Some statistical models for limited dependent variables with application to the demand for durable goods. *Econometrica: journal of the Econometric Society,* 829-844.

Craig, S. R., Helfrich, L. A., Kuhn, D. and Schwarz, M. H. (2017). Understanding fish nutrition, feeds, and feeding.

Dehejia, R. H. and Wahba, S. (2002). Propensity score-matching methods for nonexperimental causal studies. *Review of Economics and statistics*, *84*(1), 151-161.

De Silva, S. S. and Hasan, M. R. (2007). Feeds and fertilizers: the key to long-term sustainability of Asian aquaculture. FAO Fisheries Technical Paper, 497, 19.

DoF, (2022). Yearbook of Fisheries Statistics of Bangladesh, 2020-21, Bangladesh: Fisheries Resources Survey System (FRSS), Department of Fisheries. Bangladesh: Ministry of Fisheries and Livestock.

Edwards, P., Zhang, W., Belton, B. and Little, D. C. (2019). Misunderstandings, myths and mantras in aquaculture: Its contribution to world food supplies has been systematically over reported. *Marine Policy,* 106, 103547.

Engel, C. and Moffatt, P. G. (2014). dhreg, xtdhreg, and bootdhreg: Commands to implement double-hurdle regression. *The Stata Journal*, *14*(4), 778-797.

Grimm-Greenblatt, J., Pomeroy, R., Bravo-Ureta, B., Sinh, L. X., Van Hien, H. and Getchis, T. (2015). Economic analysis of alternative snakehead Channa striata feed. *Aquaculture Economics & Management*, 19(2), 192-209.

Hasan, M. R. (2010). On-farm feeding and feed management in aquaculture. FAO Aquaculture Newsletter, (45), 48.

Heckman, J. J. (1976). The common structure of statistical models of truncation, sample selection and limited dependent variables and a simple estimator for such models.

In Annals of economic and social measurement, volume 5, number 4 (pp. 475-492). NBER.

Heckman, J. J., Ichimura, H., Smith, J. A. and Todd, P. E. (1998). Characterizing selection bias using experimental data.

Heckman, J. J. and Vytlacil, E. J. (2007). Econometric evaluation of social programs, part II: Using the marginal treatment effect to organize alternative econometric estimators to evaluate social programs, and to forecast their effects in new environments. *Handbook of econometrics*, *6*, 4875-5143.

Hernandez, R., Belton, B., Reardon, T., Hu, C., Zhang, X. and Ahmed, A. (2018). The "quiet revolution" in the aquaculture value chain in Bangladesh. *Aquaculture*, 493, p. 456-468.

Ike, N. and Roseline, O. (2007). Adoption of Aquaculture Technology by Fish Farmers in Imo State of Nigeria. *Journal of Technology studies*, 33(1), 57-63.

Jahan, K. M., Belton, B., Ali, H., Dhar, G. C. and Ara, I. (2015). Aquaculture technologies in Bangladesh: An assessment of technical and economic performance and producer behavior.

Jobling, M., Gomes, E. and Dias, J. (2001). Feed types, manufacture and ingredients. *Food intake in fish*, 25-48.

Jones, A. M. (1989). A double-hurdle model of cigarette consumption. *Journal of applied econometrics*, *4*(1), 23-39.

Kazal, M. M. H., Rahman, M. S. and Rayhan, S. J. (2020). Determinants and impact of the adoption of improved management practices: case of freshwater prawn farming in Bangladesh. *Aquaculture reports,* 18, 100448.

Mamun-Ur-Rashid, M., Belton, B., Phillips, M. and Rosentrater, K. A. (2013). Improving aquaculture feed in Bangladesh: From feed ingredients to farmer profit to safe consumption. WorldFish.

Maredia, M. K., Reyes, B., Ba, M. N., Dabire, C. L., Pittendrigh, B. and Bello-Bravo, J. (2018). Can mobile phone-based animated videos induce learning and technology adoption among low-literate farmers? A field experiment in Burkina Faso. *Information Technology for Development*, 24(3), 429-460.

Mishra, A. K., Kumar, A., Joshi, P. K. and D'souza, A. (2016). Impact of contracts in high yielding varieties seed production on profits and yield: The case of Nepal. *Food Policy*, 62, 110-121.

Mohan Dey, M., Rab, M. A., Paraguas, F. J., Bhatta, R., Ferdous Alam, M., Koeshendrajana, S. and Ahmed, M. (2005). Status and economics of freshwater aquaculture in selected countries of Asia. *Aquaculture Economics & Management*, *9*(1-2), 11-37.

Munguti, J. M., Kirimi, J. G., Obiero, K. O., Ogello, E. O., Sabwa, J. A., Kyule, D. N., ... and Musalia, L. M. (2021). Critical Aspects of Aquafeed Value Chain in the Kenyan Aquaculture Sector--A Review.

Naylor, R., Fang, S. and Fanzo, J. (2023). A global view of aquaculture policy. *Food Policy*, 116, 102422.

Noltze, M., Schwarze, S. and Qaim, M. (2012). Understanding the adoption of system technologies in smallholder agriculture: The system of rice intensification (SRI) in Timor Leste. *Agricultural systems*, *108*, 64-73.

Obiero, K. O., Waidbacher, H., Nyawanda, B. O., Munguti, J. M., Manyala, J. O. and Kaunda-Arara, B. (2019). Predicting uptake of aquaculture technologies among smallholder fish farmers in Kenya. *Aquaculture International*, 27, 1689-1707.

Ogunremi, J. B. and Oladele, O. I. (2012). Adoption of aquaculture technology by fish farmers in Lagos State, Nigeria. *Life Science Journal,* 9(2), 430-434.

Olabisi, M. (2017). The impact of exporting and foreign direct investment on product innovation: evidence from Chinese manufacturers. *Contemporary Economic Policy*, 35(4), 735-750.

Petersen, E. H., Suc, N. X., Thanh, D. V. and Hien, T. T. (2011). Bioeconomic analysis of extensive mud crab farming in Vietnam and analysis of improved diets. *Aquaculture Economics & Management*, *15*(2), 83-102.

Ragasa, C., Osei-Mensah, Y. O. and Amewu, S. (2022). Impact of fish feed formulation training on feed use and farmers' income: Evidence from Ghana. *Aquaculture,* 558, 738378.

Rahman, M. S., Kazal, M. M. H. and Rayhan, S. J. (2020a). Adoption and impacts of improved mud crab fattening practices on the productivity and wellbeing of coastal farmers in Bangladesh. *Aquaculture international,* 28, 2207-2219.

Rahman, M. S., Kazal, M. M. H. and Rayhan, S. J. (2020). Impacts of the training of mud crab farmers: An adaptation strategy to cope with salinity intrusion in Bangladesh. *Marine Policy,* 120, 104159.

Rahman, M. S. and Majumder, M. K. (2021). Drivers of adoption and impacts of an eco-friendly agricultural technology in Bangladesh. *SN Business & Economics*, *1*(12), 162.

Rand, J. and Tarp, F. (2009). Impact of an aquaculture extension project in Bangladesh. *Journal of Development Effectiveness,* 1(2), 130-146.

Reyes, B., Donovan, C., Bernsten, R. H. and Maredia, M. K. (2012). Market participation and sale of potatoes by smallholder farmers in the central highlands of Angola: A Double Hurdle approach.

Rola, W. R. and Hasan, M. R. (2007). Economics of aquaculture feeding. Economics of aquaculture feeding practices in selected Asian countries, (505), 121.

Shannon, C. E. (1948). A mathematical theory of communication. *The Bell system technical journal,* 27(3), 379-423.

Smale, M., Just, R. E. and Leathers, H. D. (1994). Land allocation in HYV adoption models: an investigation of alternative explanations. *American Journal of Agricultural Economics,* 76(3), 535-546.

Tacon, A. G. J. and Metian, M. (2015). Feed matters: satisfying the feed demand of aquaculture. *Reviews in Fisheries Science & Aquaculture*, 23(1), 1–10.

Thompson, P. M., Firoz Khan, A. K. M. and Sultana, P. (2006). Comparison of aquaculture extension impacts in Bangladesh. *Aquaculture Economics & Management,* 10(1), 15-31.

Tobin, J. (1958). Estimation of relationships for limited dependent variables. *Econometrica: journal of the Econometric Society,* 24-36.

United Nations Bangladesh. (2024). Sustainable Development Goals in Bangladesh. Access on 15 May 2024. http://bangladesh.un.org/en/sdgs/2.

Wafula, B. N., Ngeno, V., Serem, A. and Kipkorir, P. (2021). Adoption and intensity of improved fish feeds use in Western Kenya. *East African Agricultural and Forestry Journal,* 85(3 & 4), 12-12.

Wooldridge, J. M. (2010). *Econometric analysis of cross section and panel data*. MIT press.

Wooldridge, J. M. (2009). Introductory Econometrics: A Formulated Approach. 4th ed. Mason, OH: South-Western.

World Economics, (2023). Bangladesh's Social Factors. Access on 23 April 2024. https://www.worldeconomics.com/ESG/Social/Bangladesh.aspx

Yi, D., Reardon, T. and Stringer, R. (2018). Shrimp aquaculture technology change in Indonesia: Are small farmers included? *Aquaculture*, 493, 436–445.

Yuan, X. (2007). Economics of aquaculture feeding practices: China. FAO FISHERIES TECHNICAL PAPER, 505, 65.

Zaher, M. and Mazid, M. A. (1995). Aquafeeds and feeding strategies in Bangladesh. *FAO Fisheries Technical Paper*, 161-180.

APPENDIX A: TABLES AND FIGURES

Formulated feed related: Table A-1 to Table A-6

Table A-1: Determinants of formulated feed adoption in sample pond

	(1)	(2)
	Double hurdle model	
Variables	Selection model (Probability of adoption)	Outcome model (Intensity of adoption)
Plot-level variables		
Fish-rice integration	0.036	-0.191***
	(0.146)	(0.038)
Fish-vegetable/fruit integration	0.320**	0.075**
	(0.138)	(0.035)
Fish only	0.223	0.096**
	(0.161)	(0.046)
Fish prawn	0.626***	0.031
	(0.178)	(0.045)
Fish Shrimp	-0.034	0.022
	(0.208)	(0.071)
Casual labor (man-days/ha)	0.0002	-0.00001
	(0.0002)	(0.00006)
Area of sample parcel (ha)	-0.214	-0.075
	(0.164)	(0.057)
Distance home (km)	-0.076	0.006
	(0.091)	(0.027)
Distance road (km)	0.240	0.031
	(0.170)	(0.048)
Household-level variables		
Dependency ratio	0.078	0.028
	(0.106)	(0.029)
Age (years)	0.005	-0.0006
	(0.005)	(0.0013)
Education (years)	0.019	0.001
	(0.013)	(0.004)
Fish-farming experience (years)	-0.002	-0.0005
	(0.008)	(0.002)
Off-farm paid (0/1)	-0.044	-0.016
	(0.113)	(0.031)
Off-farm self-activity (days)	0.0005*	-0.0001
	(0.0003)	(0.00007)

Table A-1 (cont'd)

Credit (0/1)	0.050	0.028
	(0.126)	(0.035)
Extension fisheries (0/1)	0.681**	0.056
	(0.332)	(0.069)
Owned operated area (ha)	0.086	0.050***
	(0.078)	(0.019)
Village-level variables		
Village feed suppliers (0/1)	0.379***	-0.108***
	(0.125)	(0.035)
Permanent village market (0/1)	0.233*	-0.059
	(0.130)	(0.038)
Urban travel time (minutes)	0.009*	0.002*
	(0.005)	(0.001)
Constant	-1.244***	0.478***
	(0.374)	(0.106)
lnsigma	-1.362***	
	(0.049)	
Wald $\chi2$ /F statistics	90.17***	
Observations	634	634

Note: Standard errors are in parentheses (*** p<0.01, ** p<0.05, * p<0.1)
Source: Author, based on 2020 fish and shrimp farm survey in Bangladesh

Table A-2: Factors affecting the adoption of formulated feed (Tobit model) in sample pond

Variables	(1) Tobit model (Y= formulated feed use)	(2) marginal effect from Tobit
Plot-level variables		
Fish-rice integration	-0.086**	**-0.057****
	(0.042)	(0.027)
Fish-vegetable/fruit integration	0.112***	**0.078*****
	(0.039)	(0.028)
Fish only	0.132***	**0.091*****
	(0.049)	(0.034)
Fish prawn	0.165***	**0.117*****
	(0.049)	(0.037)
Fish Shrimp	-0.009	-0.006
	(0.068)	(0.045)
Casual labor (man-days/ha)	0.00006	0.00004
	(0.00006)	(0.00004)
Area of sample parcel (ha)	-0.093*	**-0.062***
	(0.052)	(0.035)
Distance home (km)	-0.020	-0.014
	(0.028)	(0.019)
Distance road (km)	0.080	0.053
	(0.051)	(0.034)
Household-level variables		
Dependency ratio	0.039	0.026
	(0.032)	(0.021)
Age (years)	0.002	0.001
	(0.001)	(0.001)
Education (years)	0.006	0.004
	(0.004)	(0.003)
Fish-farming experience (years)	-0.0004	-0.0003
	(0.002)	(0.002)
Off-farm paid (0/1)	-0.028	-0.018
	(0.034)	(0.023)
Off-farm self-activity (days)	0.00006	0.00004
	(0.00008)	(0.00005)
Credit (0/1)	0.029	0.019
	(0.038)	(0.026)

Table A-2 (cont'd)

Extension fisheries (0/1)	0.174**	**0.128***
	(0.083)	(0.066)
Owned operated area (ha)	0.049**	**0.033****
	(0.022)	(0.015)
Village-level variables		
Village feed suppliers (0/1)	0.063*	**0.042***
	(0.038)	(0.025)
Permanent village market (0/1)	0.048	0.032
	(0.040)	(0.026)
Urban travel time (minutes)	0.003***	0.002***
	(0.001)	(0.001)
var(e.formulated feed intensity)	0.145***	
	(0.011)	
Constant	-0.256*	
	(0.111)	
Observations	634	634

Note: Standard errors are in parentheses (*** p<0.01, ** p<0.05, * p<0.1)
Source: Author, based on 2020 fish and shrimp farm survey in Bangladesh

Table A-3: Marginal effects on binary use of formulated feed (probit) in sample pond with factors at different levels

	(1)	(2)	(3)
	Y= formulated feed use (0/1)		
Variables	With plot-level variables	With Household-level variables	With Village-level variables
Fish-rice integration	0.065	0.064	0.013
	(0.054)	(0.055)	(0.053)
Fish-vegetable/fruit integration	0.126***	0.122***	0.113***
	(0.048)	(0.043)	(0.043)
Fish only	0.107	0.070	0.080
	(0.083)	(0.085)	(0.073)
Fish prawn	0.226***	0.208***	0.207***
	(0.074)	(0.076)	(0.074)
Fish Shrimp	-0.036	-0.049	-0.013
	(0.085)	(0.078)	(0.079)
Casual labor (man-days/ha)	0.00003	0.00005	0.00007
	(0.00008)	(0.00008)	(0.00008)
Area of sample parcel (ha)	-0.034	-0.095*	-0.078*
	(0.050)	(0.051)	(0.047)
Distance home (km)	-0.017	-0.016	-0.028
	(0.031)	(0.032)	(0.027)
Distance road (km)	0.078	0.096*	0.087
	(0.057)	(0.057)	(0.057)
Dependency ratio		0.024	0.028
		(0.039)	(0.039)
Age (years)		0.002	0.002
		(0.002)	(0.002)
Education (years)		0.008**	0.007**
		(0.004)	(0.003)
Fish-farming experience (years)		-0.001	-0.0007
		(0.003)	(0.003)
Off-farm paid (0/1)		-0.012	-0.016
		(0.042)	(0.041)
Off-farm self-activity (days)		0.0003***	0.0002*
		(0.00009)	(0.00009)
Owned operated area (ha)		0.036	0.031
		(0.024)	(0.022)
Credit (0/1)		0.016	0.018
		(0.052)	(0.054)

Table A-3 (cont'd)

Extension fisheries (0/1)		0.176***	0.204***
		(0.059)	(0.048)
Village feed suppliers (0/1)			0.141***
			(0.055)
Permanent village market (0/1)			0.086
			(0.070)
Urban travel time (minutes)			0.003
			(0.003)
Observations	634	634	634

Note: Standard errors are clustered at village level in parentheses. *** p<0.01, ** p<0.05, * p<0.1
Source: Author, based on 2020 fish and shrimp farm survey in Bangladesh

Table A-4: Marginal effects on intensity of formulated feed use (truncated) in sample pond with factors at different levels

	(1)	(2)	(3)
	Y= formulated feed use intensity		
Variables	With plot-level variables	With Household-level variables	With Village-level variables
Fish-rice integration	-0.153***	-0.154***	-0.141***
	(0.034)	(0.034)	(0.029)
Fish-vegetable/fruit integration	0.041	0.054*	0.057*
	(0.028)	(0.028)	(0.030)
Fish only	0.082	0.072	0.074
	(0.051)	(0.052)	(0.053)
Fish prawn	0.024	0.018	0.024
	(0.055)	(0.052)	(0.050)
Fish Shrimp	0.003	0.015	0.017
	(0.053)	(0.056)	(0.046)
Casual labor (man-days/ha)	0.00003	0.00001	-0.000008
	(0.00004)	(0.00004)	(0.00003)
Area of sample parcel (ha)	0.002	-0.055	-0.057
	(0.038)	(0.043)	(0.043)
Distance home (km)	-0.012	-0.004	0.004
	(0.024)	(0.024)	(0.023)
Distance road (km)	0.014	0.020	0.023
	(0.033)	(0.033)	(0.033)
Dependency ratio		0.022	0.021
		(0.023)	(0.024)
Age (years)		-0.0003	-0.0004
		(0.001)	(0.001)
Education (years)		0.001	0.001
		(0.003)	(0.003)
Fish-farming experience (years)		0.00006	-0.0004
		(0.002)	(0.002)
Off-farm paid (0/1)		-0.016	-0.012
		(0.028)	(0.027)
Off-farm self-activity (days)		-0.0001*	-0.00008
		(0.00006)	(0.00005)
Owned operated area (ha)		0.041***	0.038***
		(0.012)	(0.012)
Credit (0/1)		0.027	0.021
		(0.028)	(0.028)

Table A-4 (cont'd)

Extension fisheries (0/1)		0.063	0.044
		(0.040)	(0.044)
Village feed suppliers (0/1)			-0.085**
			(0.038)
Permanent village market (0/1)			-0.046
			(0.047)
Urban travel time (minutes)			0.002
			(0.001)
Observations	410	410	410

Note: Standard errors are clustered at village level in parentheses. *** p<0.01, ** p<0.05, * p<0.1
Source: Author, based on 2020 fish and shrimp farm survey in Bangladesh

Table A-5: Marginal effects on formulated feed adoption by households with only 1 pond

Variables	(1) Marginal effect on binary adoption (Probit)	(2) Conditional marginal effect (Truncated model)	(3) Unconditional marginal effect (Double hurdle)
Plot-level variables			
Fish-rice integration	0.108	-0.120***	-0.034
	(0.069)	(0.033)	(0.034)
Fish-vegetable/fruit integration	0.123**	0.021	0.059**
	(0.056)	(0.032)	(0.025)
Fish only	0.024	-0.008	0.004
	(0.084)	(0.057)	(0.045)
Fish prawn	0.240***	0.005	0.102
	(0.082)	(0.059)	(0.063)
Fish shrimp	0.105	-0.028	0.023
	(0.068)	(0.052)	(0.045)
Casual labor (man-days/ha)	0.0002	-0.0001	0.00001
	(0.0001)	(0.00005)	(0.00005)
Area of sample parcel (ha)	-0.073	-0.082*	-0.077*
	(0.074)	(0.049)	(0.041)
Distance home (km)	-0.064*	0.009	-0.018
	(0.036)	(0.031)	(0.024)
Distance road (km)	0.079	0.007	0.034
	(0.092)	(0.044)	(0.043)
Household-level variables			
Dependency ratio	0.078	0.045	0.056**
	(0.048)	(0.035)	(0.026)
Age (years)	0.004	0.001	0.002**
	(0.002)	(0.001)	(0.001)
Education (years)	0.008	-0.002	0.002
	(0.006)	(0.004)	(0.003)
Fish-farming experience (years)	0.0009	-0.002	-0.0006
	(0.004)	(0.002)	(0.002)
Off-farm paid (0/1)	-0.080	-0.008	-0.035
	(0.054)	(0.031)	(0.031)
Off-farm self-activity (days)	0.0003**	-0.00001	0.00005
	(0.0001)	(0.0001)	(0.00007)
Owned operated area (ha)	0.017	0.049*	0.037**
	(0.030)	(0.026)	(0.019)
Credit (0/1)	0.062	-0.014	0.015
	(0.072)	(0.038)	(0.038)

Table A-5 (cont'd)

Extension fisheries (0/1)	0.272***	0.101*	0.192**
	(0.067)	(0.060)	(0.077)
Village-level variables			
Village feed suppliers (0/1)	0.131*	-0.035	0.026
	(0.070)	(0.049)	(0.040)
Permanent village market (0/1)	0.129*	-0.073	0.003
	(0.068)	(0.068)	(0.043)
Urban travel time (minutes)	0.003	0.003***	0.003**
	(0.003)	(0.001)	(0.001)
Observations	380	235	380

Note: Robust standard errors are in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table A-6: Marginal effects on formulated feed adoption by households with only 1 pond including few households with >1 pond

Variables	(1) Marginal effect on binary adoption (Probit)	(2) Conditional marginal effect (Truncated model)	(3) Unconditional marginal effect (Double hurdle)
Plot-level variables			
Fish-rice integration	0.112*	-0.111***	-0.027
	(0.061)	(0.034)	(0.034)
Fish-vegetable/fruit integration	0.119**	0.026	0.062**
	(0.055)	(0.032)	(0.024)
Fish only	0.037	-0.004	0.012
	(0.084)	(0.058)	(0.045)
Fish prawn	0.237***	-0.002	0.099
	(0.081)	(0.060)	(0.065)
Fish shrimp	0.100	-0.028	0.022
	(0.068)	(0.050)	(0.044)
Casual labor (man-days/ha)	0.0002	-0.00008	0.00007
	(0.0001)	(0.00005)	(0.00005)
Area of sample parcel (ha)	-0.085	-0.098**	-0.093**
	(0.076)	(0.050)	(0.042)
Distance home (km)	-0.062*	0.020	-0.011
	(0.034)	(0.032)	(0.024)
Distance road (km)	0.089	-0.009	0.028
	(0.091)	(0.045)	(0.045)
Household-level variables			
Dependency ratio	0.076	0.041	0.054**
	(0.047)	(0.035)	(0.026)
Age (years)	0.003	0.001	0.002*
	(0.002)	(0.001)	(0.001)
Education (years)	0.007	-0.002	0.001
	(0.005)	(0.004)	(0.003)
Fish-farming experience (years)	0.002	-0.001	0.0004
	(0.004)	(0.002)	(0.002)
Off-farm paid (0/1)	-0.071	-0.008	-0.032
	(0.051)	(0.028)	(0.028)
Off-farm self-activity (days)	0.0003**	-0.0001	0.00003
	(0.0001)	(0.00007)	(0.00007)
Owned operated area (ha)	0.028	0.062**	0.049**
	(0.033)	(0.025)	(0.019)

Table A-6 (cont'd)

Credit (0/1)	0.060	-0.013	0.015
	(0.073)	(0.038)	(0.039)
Extension fisheries (0/1)	0.263***	0.099*	0.188**
	(0.072)	(0.060)	(0.079)
Village-level variables			
Village feed suppliers (0/1)	0.127*	-0.034	0.026
	(0.068)	(0.047)	(0.039)
Permanent village market (0/1)	0.125*	-0.079	-0.002
	(0.068)	(0.071)	(0.046)
Urban travel time (minutes)	0.003	0.003***	0.003**
	(0.003)	(0.001)	(0.001)
Observations	386	240	386

Note: Robust standard errors are in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Floating pellets related: Table A-7 to Table A-12

Table A-7: Determinants of floating feed adoption (conditional) in sample pond

	(1)	(2)
	Double hurdle model	
Variables	Selection model (Probability of adoption)	Outcome model (Intensity of adoption)
Plot-level variables		
Integrated	0.268*	-0.138**
	(0.161)	(0.066)
Fish only	0.668***	0.330***
	(0.217)	(0.096)
Fish prawn	0.118	0.013
	(0.196)	(0.096)
Fish shrimp	-0.187	0.248
	(0.344)	(0.191)
Catfish	0.395**	-0.007
	(0.181)	(0.071)
Casual labor (man-days/ha)	0.001	0.0001
	(0.001)	(0.0005)
Area of sample parcel (ha)	-0.511*	-0.025
	(0.275)	(0.143)
Distance home (km)	-0.170	-0.126*
	(0.132)	(0.067)
Distance road (km)	0.510**	-0.016
	(0.229)	(0.103)
Flood (0/1)	0.391***	-0.045
	(0.149)	(0.060)
Household-level variables		
Dependency ratio	0.200	0.082
	(0.140)	(0.057)
Age (years)	-0.013**	-0.0004
	(0.006)	(0.002)
Education (years)	0.003	0.010
	(0.016)	(0.006)
Fish-farming experience (years)	-0.009	0.00004
	(0.010)	(0.004)

Table A-7 (cont'd)

Off-farm paid (0/1)	0.049	-0.150**
	(0.142)	(0.059)
Off-farm self-activity (days)	-0.0005	-0.0003*
	(0.0003)	(0.0001)
Credit (0/1)	0.441***	0.064
	(0.161)	(0.063)
Extension fisheries (0/1)	0.313	0.149
	(0.334)	(0.121)
Owned operated area (ha)	0.163*	0.044
	(0.094)	(0.029)
Village-level variables		
Village feed suppliers (0/1)	0.364**	-0.055
	(0.175)	(0.074)
Village market	1.037**	-0.532**
	(0.403)	(0.238)
Urban travel time (minutes)	0.017***	0.009***
	(0.006)	(0.002)
Constant	-2.042***	0.462
	(0.594)	(0.281)
lnsigma	-1.288***	
	(0.087)	
Wald $\chi2$ /F statistics	82.68***	
Observations	410	410

Note: Standard errors are in parentheses (*** p<0.01, ** p<0.05, * p<0.1)
Source: Author, based on 2020 fish and shrimp farm survey in Bangladesh

Table A-8: Factors affecting the adoption of floating feed (conditional) in sample pond (Tobit)

Variables	(1) Tobit model (Y= floating feed use)	(2) Marginal effect from Tobit
Plot-level variables		
Integrated	-0.002	-0.001
	(0.047)	(0.024)
Fish only	0.286***	0.154***
	(0.063)	(0.036)
Fish prawn	0.048	0.025
	(0.058)	(0.030)
Fish shrimp	-0.015	-0.007
	(0.108)	(0.053)
Catfish	0.084	0.040
	(0.054)	(0.025)
Casual labor (man-days/ha)	0.0003	0.0002
	(0.0004)	(0.0002)
Area of sample parcel (ha)	-0.174**	-0.088**
	(0.082)	(0.041)
Distance home (km)	-0.072*	-0.036*
	(0.040)	(0.020)
Distance road (km)	0.128**	0.064**
	(0.065)	(0.033)
Flood (0/1)	0.082*	0.042*
	(0.043)	(0.022)
Household-level variables		
Dependency ratio	0.072*	0.036*
	(0.040)	(0.020)
Age (years)	-0.004**	-0.002**
	(0.002)	(0.001)
Education (years)	0.004	0.002
	(0.005)	(0.002)
Fish-farming experience (years)	-0.003	-0.001
	(0.003)	(0.002)
Off-farm paid (0/1)	-0.026	-0.013
	(0.041)	(0.021)
Off-farm self-activity (days)	-0.0002**	-0.0001**
	(0.00009)	(0.00005)
Credit (0/1)	0.137***	0.073***
	(0.046)	(0.025)
Extension fisheries (0/1)	0.132	0.074
	(0.095)	(0.059)

Table A-8 (cont'd)

Owned operated area (ha)	0.067***	0.034***
	(0.025)	(0.013)
Village-level variables		
Village feed suppliers (0/1)	0.087	0.042*
	(0.053)	(0.024)
Village market	0.187	0.079*
	(0.126)	(0.043)
Urban travel time (minutes)	0.008***	0.004***
	(0.002)	(0.001)
var(e.floating feed intensity)	0.121***	
	(0.013)	
Constant	-0.496***	NA
	(0.181)	
Observations	410	410

Note: Standard errors are in parentheses (*** p<0.01, ** p<0.05, * p<0.1)
Source: Author, based on 2020 fish and shrimp farm survey in Bangladesh

Table A-9: Marginal effects on binary use of floating feed (conditional) in sample pond with factors at different levels (selection model: Probit)

	(1)	(2)	(3)
	Y= floating pelleted feed use (0/1)		
Variables	With plot-level variables	With Household-level variables	With Village-level variables
Integrated	0.108*	0.132**	0.107*
	(0.064)	(0.066)	(0.064)
Fish only	0.183*	0.209**	0.261***
	(0.101)	(0.097)	(0.092)
Fish prawn	-0.023	-0.025	0.047
	(0.099)	(0.099)	(0.116)
Fish shrimp	-0.188	-0.152	-0.074
	(0.115)	(0.124)	(0.133)
Catfish	0.159**	0.178**	0.155*
	(0.081)	(0.082)	(0.082)
Casual labor (man-days/ha)	0.001	0.0003	0.001
	(0.001)	(0.001)	(0.001)
Area of sample parcel (ha)	-0.124	-0.230**	-0.204**
	(0.078)	(0.098)	(0.103)
Distance home (km)	-0.092*	-0.082*	-0.068*
	(0.051)	(0.045)	(0.039)
Distance road (km)	0.235***	0.242***	0.203***
	(0.087)	(0.078)	(0.073)
Flood (0/1)	0.207***	0.197***	0.155**
	(0.058)	(0.063)	(0.069)
Dependency ratio		0.061	0.080
		(0.061)	(0.063)
Age (years)		-0.005**	-0.005**
		(0.003)	(0.002)
Education (years)		0.004	0.001
		(0.006)	(0.006)
Fish-farming experience (years)		-0.001	-0.004
		(0.005)	(0.005)
Owned operated area (ha)		0.074**	0.065**
		(0.029)	(0.027)
Off-farm paid (0/1)		0.014	0.019
		(0.054)	(0.057)
Off-farm self-activity (days)		-0.0001	-0.0002
		(0.0002)	(0.0002)

Table A-9 (cont'd)

Credit (0/1)		0.169***	0.174***
		(0.065)	(0.065)
Extension fisheries (0/1)		0.098	0.123
		(0.137)	(0.135)
Village feed suppliers (0/1)			0.144
			(0.088)
Village market			0.358***
			(0.079)
Urban travel time (minutes)			0.007**
			(0.003)
Observations	410	410	410

Note: Standard errors are clustered at village level in parentheses. ***p<0.01, **p<0.05, * p<0.1
Source: Author, based on 2020 fish and shrimp farm survey in Bangladesh

Table A-10: Marginal effects on intensity of formulated feed use in sample pond with factors at different levels (truncated model)

	(1)	(2)	(3)
	Y= floating pelleted feed use intensity		
Variables	With plot-level variables	With Household-level variables	With Village-level variables
Integrated	-0.081**	-0.074*	-0.075*
	(0.040)	(0.039)	(0.042)
Fish only	0.144**	0.156**	0.180***
	(0.059)	(0.061)	(0.052)
Fish prawn	0.027	0.025	0.007
	(0.093)	(0.084)	(0.056)
Fish shrimp	0.024	0.100	0.155
	(0.113)	(0.111)	(0.117)
Catfish	-0.025	-0.006	-0.004
	(0.054)	(0.057)	(0.057)
Casual labor (man-days/ha)	-0.0002	-0.0003	0.00006
	(0.0004)	(0.0004)	(0.0003)
Area of sample parcel (ha)	0.021	-0.053	-0.013
	(0.085)	(0.080)	(0.084)
Distance home (km)	-0.094	-0.074	-0.068
	(0.064)	(0.052)	(0.042)
Distance road (km)	-0.049	-0.025	-0.009
	(0.069)	(0.059)	(0.059)
Flood (0/1)	-0.035	-0.012	-0.024
	(0.036)	(0.036)	(0.032)
Dependency ratio		0.029	0.044
		(0.023)	(0.027)
Age (years)		0.0002	-0.0002
		(0.001)	(0.002)
Education (years)		0.008***	0.006**
		(0.003)	(0.003)
Fish-farming experience (years)		0.001	0.00002
		(0.002)	(0.002)
Owned operated area (ha)		0.029**	0.024**
		(0.012)	(0.011)
Off-farm paid (0/1)		-0.062*	-0.079**
		(0.034)	(0.033)
Off-farm self-activity (days)		-0.00004	-0.0001*
		(0.00008)	(0.00007)

Table A-10 (cont'd)

Credit (0/1)		0.044	0.035
		(0.038)	(0.035)
Extension fisheries (0/1)		0.055	0.088
		(0.086)	(0.105)
Village feed suppliers (0/1)			-0.030
			(0.040)
Village market			-0.380***
			(0.088)
Urban travel time (minutes)			0.005***
			(0.001)
Observations	207	207	207

Note: Standard errors are clustered at village level in parentheses. ***p<0.01, ** p<0.05, * p<0.1
Source: Author, based on 2020 fish and shrimp farm survey in Bangladesh

Table A-11: Marginal effects on floating feed adoption conditional on formulated feed use by households with only 1 pond

Variables	(1)# Marginal effect on binary adoption (Probit)	(2) Conditional marginal effect (Truncated model)	(3) Unconditional marginal effect (Double hurdle)
Plot-level variables			
Integrated	0.013	-0.111**	-0.048*
	(0.072)	(0.045)	(0.028)
Fish only	0.371***	0.045	0.109**
	(0.112)	(0.072)	(0.044)
Fish prawn	0.160	-0.001	0.036
	(0.156)	(0.070)	(0.042)
Fish shrimp	-0.001	0.265*	0.099
	(0.164)	(0.151)	(0.064)
Catfish	0.185*	0.025	0.056*
	(0.102)	(0.047)	(0.032)
Casual labor (man-days/ha)	0.002*	-0.0005	0.0001
	(0.001)	(0.0005)	(0.0003)
Area of sample parcel (ha)	-0.237	0.004	-0.053
	(0.149)	(0.110)	(0.065)
Distance home (km)	0.016	-0.093	-0.039
	(0.067)	(0.061)	(0.034)
Distance road (km)	0.088	-0.047	-0.002
	(0.154)	(0.083)	(0.050)
Flood (0/1)	0.184**	-0.005	0.040
	(0.087)	(0.042)	(0.026)
Household-level variables			
Dependency ratio	0.054	0.052	0.036
	(0.092)	(0.041)	(0.025)
Age (years)	-0.002	0.001	0.0002
	(0.003)	(0.002)	(0.001)
Education (years)	0.012	0.009*	0.007**
	(0.010)	(0.005)	(0.003)
Fish-farming experience (years)	-0.004	-0.001	-0.001
	(0.006)	(0.003)	(0.002)
Owned operated area (ha)	-0.033	-0.094**	-0.052**
	(0.080)	(0.039)	(0.026)
Off-farm paid (0/1)	-0.0006***	-0.0002**	-0.0002***
	(0.0002)	(0.0001)	(0.0001)
Off-farm self-activity (days)	0.055	0.019	0.022
	(0.055)	(0.024)	(0.019)

Table A-11 (cont'd)

Credit (0/1)	0.305***	-0.051	0.047
	(0.101)	(0.049)	(0.030)
Extension fisheries (0/1)	0.232	0.173*	0.123**
	(0.179)	(0.099)	(0.052)
Village-level variables			
Village feed suppliers (0/1)	0.160*	-0.033	0.023
	(0.096)	(0.053)	(0.030)
Village market	0.427***	-0.557	-0.042
	(0.068)	(0.352)	(0.109)
Urban travel time (minutes)	0.009***	0.006***	0.005***
	(0.003)	(0.001)	(0.001)
Observations	235	111	235

Note: Standard errors are in parentheses (*** p<0.01, ** p<0.05, * p<0.1). #Standard errors are clustered at village level.

Table A-12: Marginal effects on floating feed adoption conditional on formulated feed use by households with only 1 pond including a few households with >1 pond

Variables	(1)# Marginal effect on binary adoption (Probit)	(2) Conditional marginal effect (Truncated model)	(3) Unconditional marginal effect (Double hurdle)
Plot-level variables			
Integrated	0.005	-0.116***	-0.051*
	(0.068)	(0.044)	(0.028)
Fish only	0.370***	0.053	0.113***
	(0.113)	(0.071)	(0.043)
Fish prawn	0.178	0.002	0.042
	(0.154)	(0.070)	(0.042)
Fish shrimp	-0.006	0.261*	0.097
	(0.163)	(0.149)	(0.063)
Catfish	0.208**	0.023	0.061**
	(0.100)	(0.047)	(0.031)
Casual labor (man-days/ha)	0.001*	-0.0004	0.0001
	(0.0008)	(0.0005)	(0.0003)
Area of sample parcel (ha)	-0.214	0.003	-0.048
	(0.148)	(0.109)	(0.064)
Distance home (km)	-0.015	-0.099*	-0.050
	(0.064)	(0.060)	(0.033)
Distance road (km)	0.145	-0.028	0.021
	(0.147)	(0.078)	(0.047)
Flood (0/1)	0.176**	-0.007	0.038
	(0.089)	(0.042)	(0.026)
Household-level variables			
Dependency ratio	0.051	0.049	0.034
	(0.088)	(0.040)	(0.025)
Age (years)	-0.002	0.0013	0.00008
	(0.003)	(0.002)	(0.001)
Education (years)	0.012	0.009*	0.007**
	(0.010)	(0.005)	(0.003)
Fish-farming experience (years)	-0.004	-0.001	-0.001
	(0.006)	(0.003)	(0.002)
Owned operated area (ha)	0.030	0.018	0.015
	(0.055)	(0.024)	(0.019)
Off-farm paid (0/1)	-0.029	-0.097**	-0.052**
	(0.078)	(0.038)	(0.026)
Off-farm self-activity (days)	-0.0006***	-0.0002**	-0.0002***
	(0.0002)	(0.0001)	(0.00006)

Table A-12 (cont'd)

Credit (0/1)	0.308***	-0.047	0.051*
	(0.100)	(0.049)	(0.030)
Extension fisheries (0/1)	0.235	0.165*	0.122**
	(0.180)	(0.097)	(0.052)
Village-level variables			
Village feed suppliers (0/1)	0.141	-0.036	0.017
	(0.091)	(0.052)	(0.030)
Village market	0.412***	-0.560	-0.053
	(0.071)	(0.348)	(0.109)
Urban travel time (minutes)	0.009***	0.006***	0.005***
	(0.003)	(0.001)	(0.001)
Observations	240	113	240

Note: Standard errors are in parentheses (*** p<0.01, ** p<0.05, * p<0.1). #Standard errors are clustered at village level

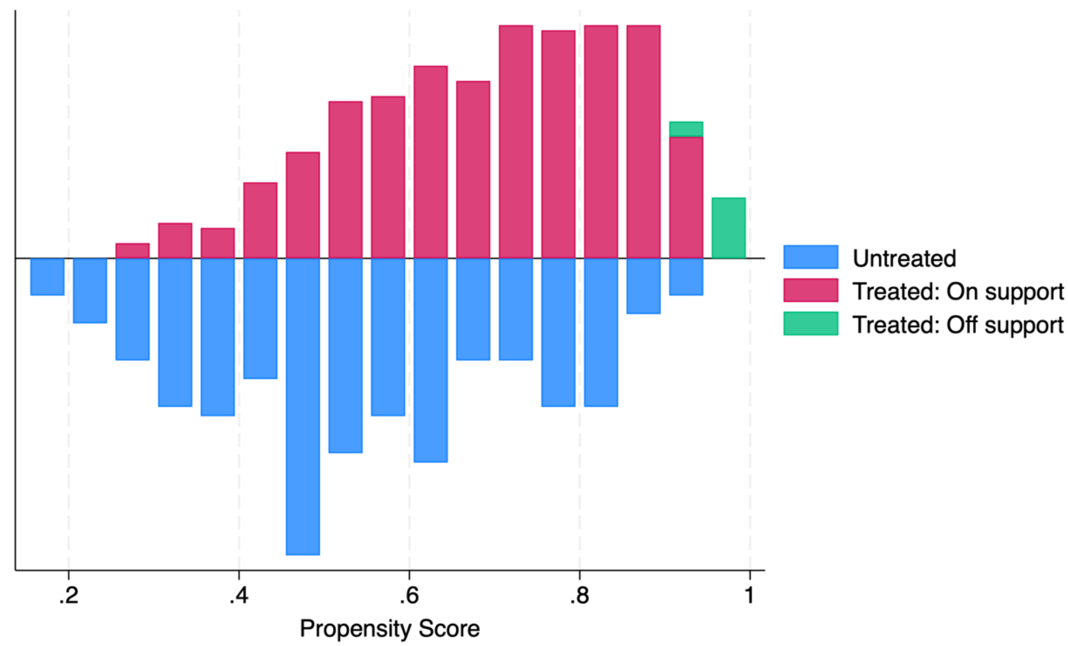

Figure A-1: Propensity score and common support of formulated feed adoption

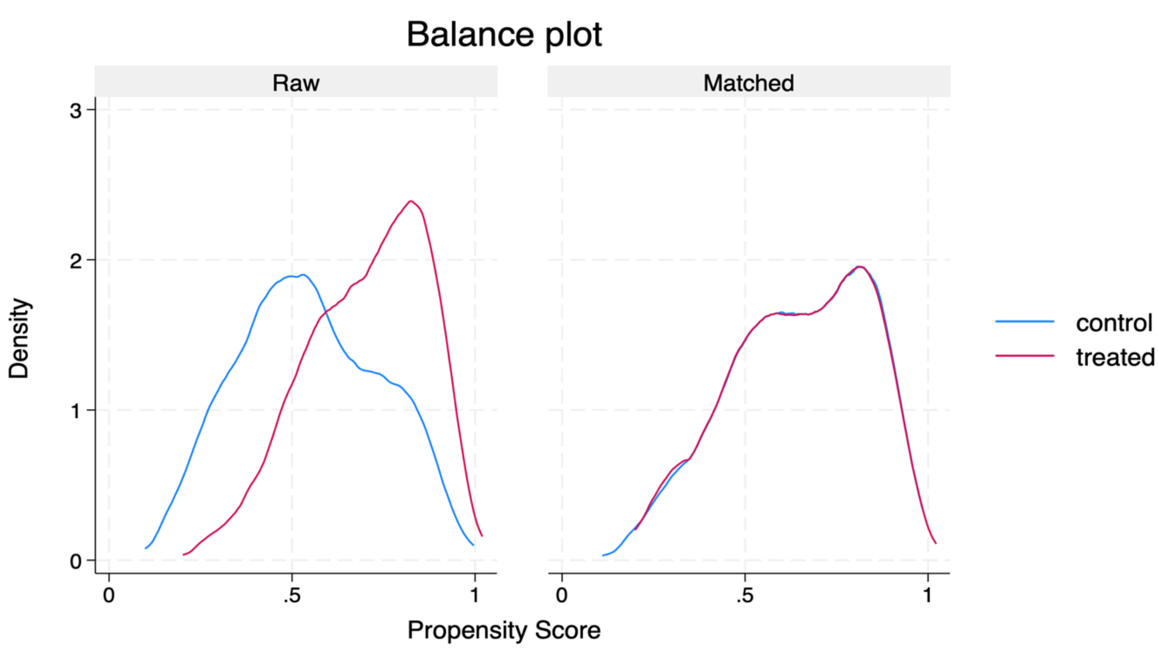

Figure A-2: Balance plot of covariates for formulated feed adoption

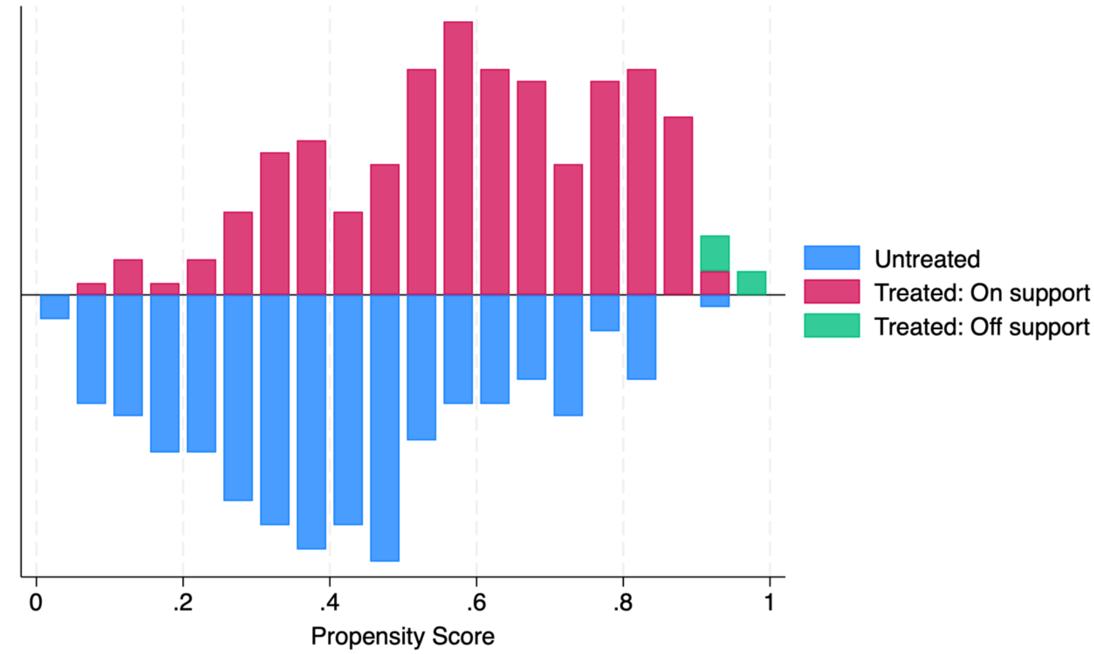

Figure A-3: Propensity score and common support of floating feed adoption (conditional)

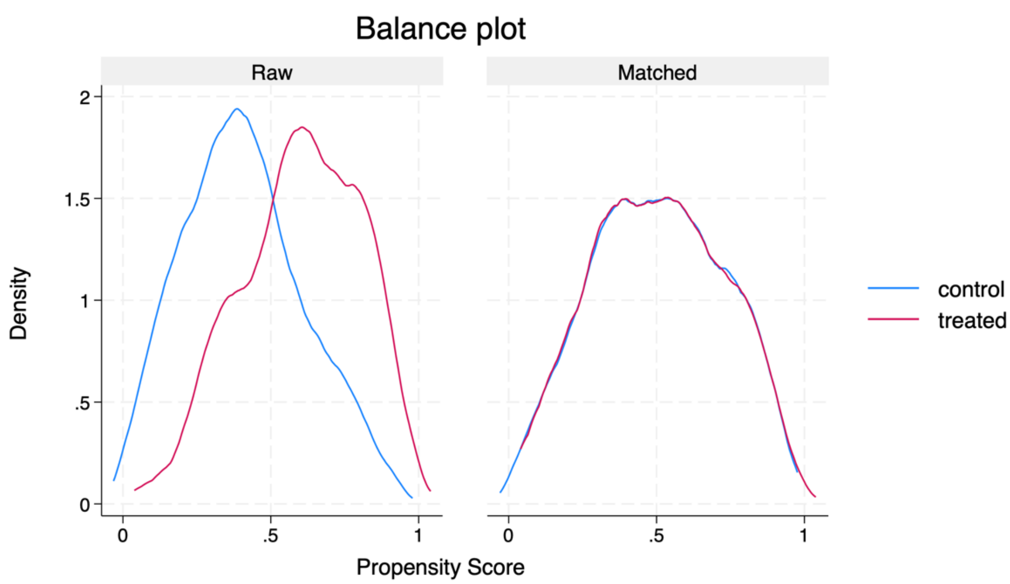

Figure A-4: Balance plot of covariates for floating feed adoption (conditional)

Table A-13: Balancing test of covariates for formulated feed adoption

	Standardized differences		Variance ratio	
	Raw	Matched	Raw	Matched
Fish-rice integration	0.354	0.007	1.386	1.005
Fish-vegetable/fruit integration	0.496	-0.020	1.605	0.986
Fish only	0.042	-0.094	1.023	0.953
Fish prawn	0.525	0.071	2.250	1.094
Fish shrimp	-0.257	0.056	0.474	1.179
Area of sample parcel (ha)	-0.183	0.087	0.383	0.601
Distance home (km)	-0.093	0.059	0.822	1.062
Distance road (km)	0.142	0.108	1.211	1.140
Flood (0/1)	-0.005	-0.016	0.996	0.992
Dependency ratio	0.107	0.084	0.804	0.781
Age (years)	0.017	-0.133	1.090	0.962
Education (years)	0.104	0.067	0.982	0.896
Fish-farming experience (years)	-0.067	0.084	0.857	1.041
Off-farm paid (0/1)	-0.110	-0.114	0.980	0.983
Off-farm self-activity (days)	0.308	-0.022	1.033	1.033
Owned operated area (ha)	0.036	0.070	0.801	1.329
Credit (0/1)	-0.091	0.066	0.920	1.063
Extension fisheries (0/1)	0.132	0.137	2.021	2.346
Village feed suppliers (0/1)	0.391	-0.052	0.745	1.048
Village market	0.314	-0.079	0.748	1.088
Urban travel time (minutes)	0.280	-0.029	1.525	1.349

Table A-14: Balancing test of covariates for floating feed adoption conditional on formulated feed use

	Standardized differences		Variance ratio	
	Raw	Matched	Raw	Matched
Integrated	0.224	-0.147	0.957	1.017
Fish only	0.260	0.105	1.155	1.050
Fish prawn	-0.024	-0.005	0.981	0.995
Fish shrimp	-0.298	0.030	0.278	1.111
Area of sample parcel (ha)	-0.259	-0.131	0.364	0.555
Distance road (km)	0.169	-0.019	1.441	0.929
Flood (0/1)	0.412	0	1.212	1
Disease (0/1)	-0.100	-0.021	0.901	0.982
Dependency ratio	0.177	-0.031	0.950	0.736
Age (years)	-0.224	0.069	1.154	1.304
Education (years)	0.038	-0.067	1.250	1.046
Fish-farming experience (years)	-0.148	-0.026	1.102	1.307
Off-farm paid (0/1)	-0.007	0.069	0.998	1.018
Off-farm self-activity (days)	-0.049	-0.071	1.058	0.812
Owned operated area (ha)	0.031	0.020	1.686	1.612
Credit (0/1)	0.263	0.027	1.309	1.027
Extension fisheries (0/1)	0.019	0.011	1.085	1.047
Village feed suppliers (0/1)	0.311	0.011	0.677	0.988
Village market	0.057	-0.070	0.927	1.097
Urban travel time (minutes)	0.442	-0.089	1.832	0.896

Table A-15: Financial analysis of aquaculture (pond polyculture)

Item	Amount kg/ha	Price BDT/kg	Total BDT/ha
A. Production (gross revenue)			**352765.8**
a. Stocking costs kg			84188.79
b. Feed costs(i+ii+iii)			114246.66
i. Formulated feed	1544.016	43.423	67045.81
ii. Traditional feed	1651.881	28.574	47200.85
iii. Feed transport			1055.64
c. Non-feed items			14665.89
d. Hired labor costs			34838.47
e. Harvest costs			3519.41
B. Production costs (a+b+c+d+e)			251459.22
C. Last transaction costs			2521.67
Gross margin (A-B-C)			98784.91
Gross margin in USD/ha	1176.01		

Source: Author, based on 2020 fish and shrimp farm survey in Bangladesh

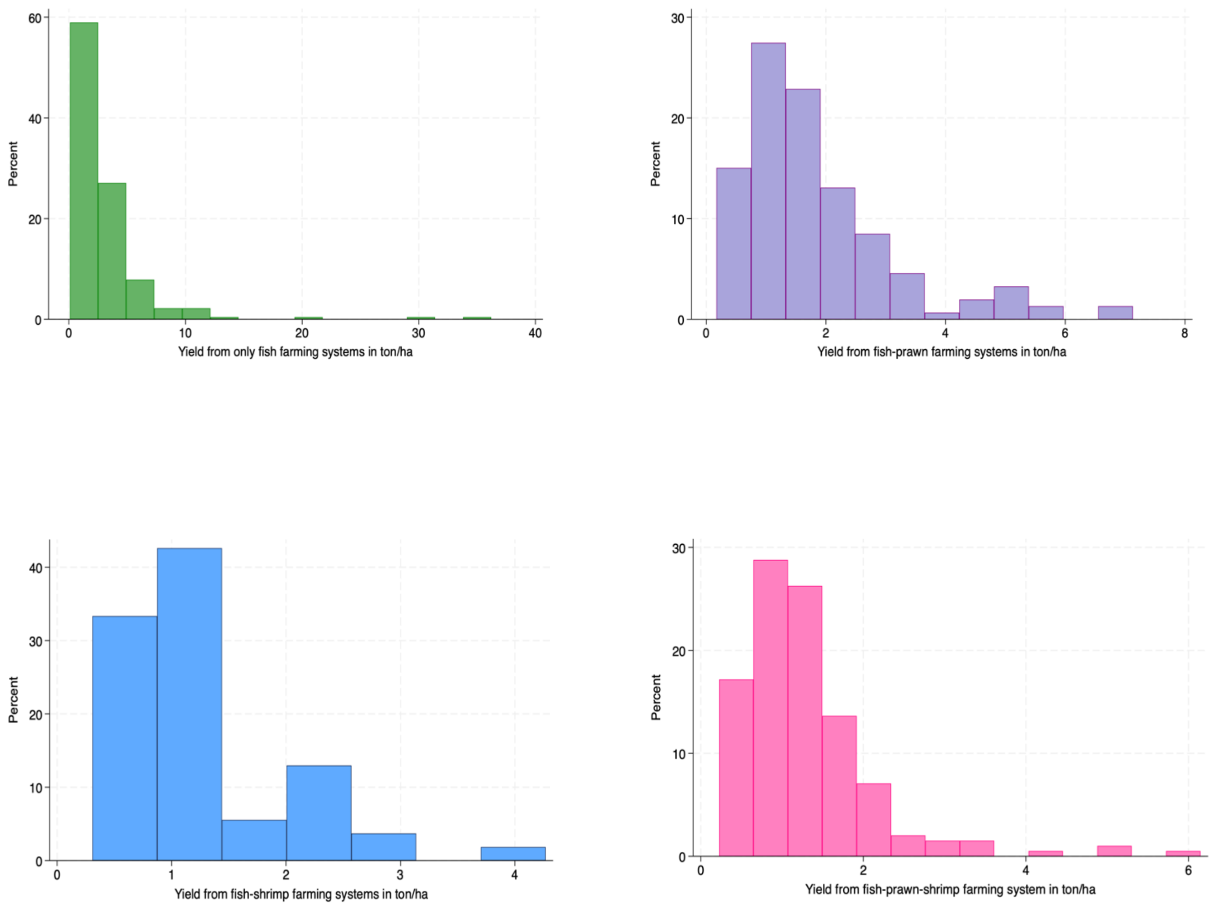

Figure A-5: Yield from aquaculture by farming systems

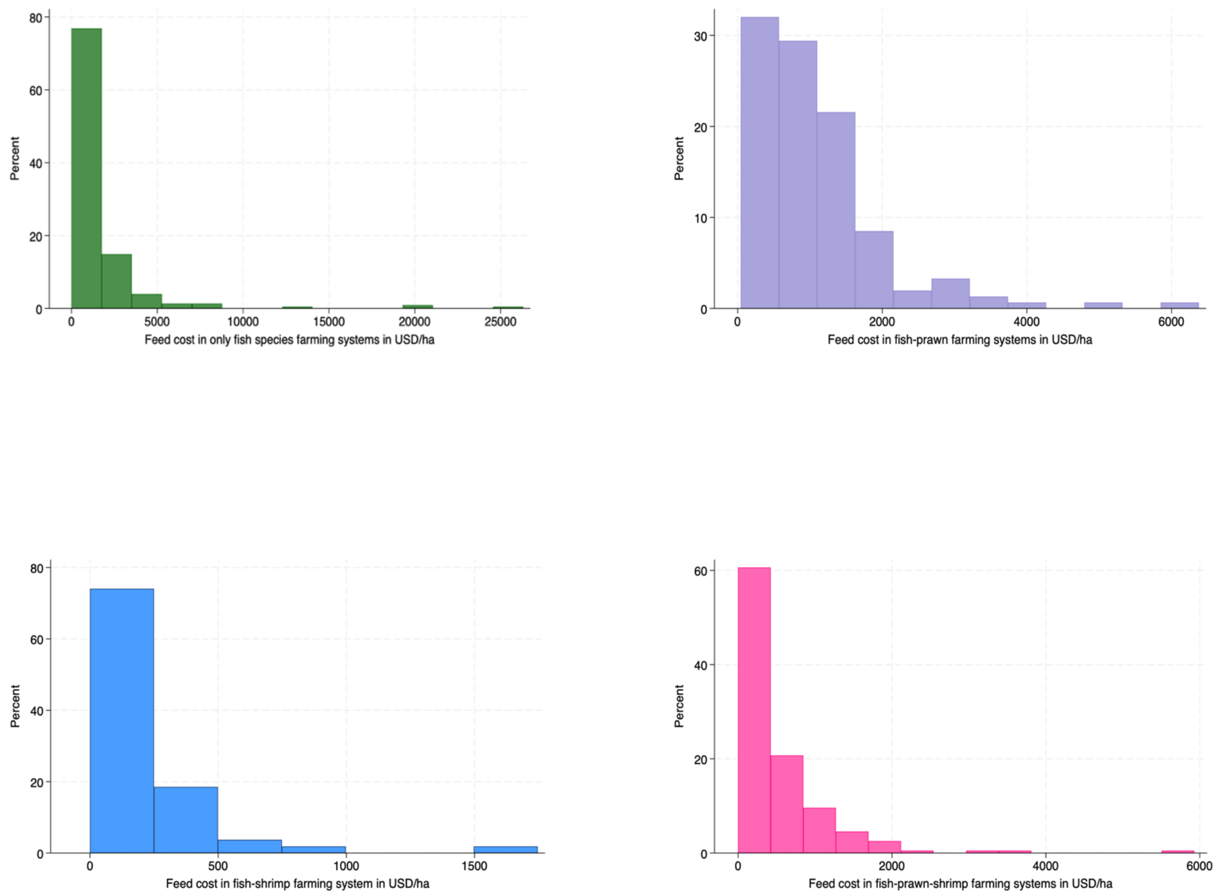

Figure A-6: Feed costs in aquaculture by farming systems

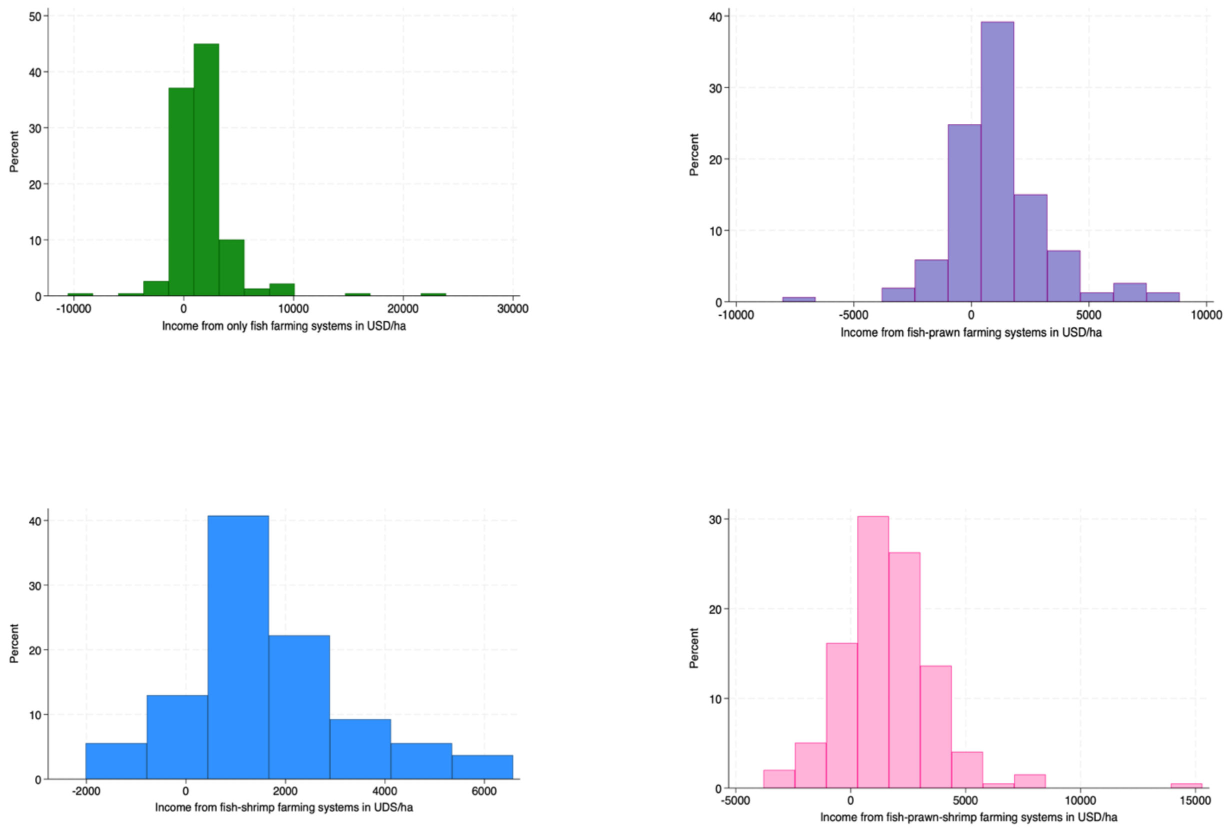

Figure A-7: Income from aquaculture by farming systems