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Performance of emergent aquaculture technologies in Myanmar; challenges and opportunities

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ABSTRACT

This paper assesses the performance of small-scale aquaculture technologies and factors influencing production, associated income and fish consumption of such technologies within agri-food farming systems in Myanmar. Farmer participatory research carried out between May 2017 and December 2018 showed that fish production could be substantially increased using available yet hitherto unused water resources through adoption of improved extensive aquaculture technologies. The technologies were tested in existing earthen ponds, *Chan myaung* (garden-irrigation systems) and WISH ponds (Water and Fish artificial ponds lined with tarpaulin). The *Chan Myaung* and WISH pond technologies were adapted and introduced in rural and urban contexts respectively. Both systems demonstrated considerable potential as a source of additional household income and food with potential for wider adoption in Myanmar. Urban households from the Central Dry Zone (CD), Upper Myanmar benefited more than rural households involved in this trial in the Ayeyarwady Delta (AD) through enhanced direct consumption of fish while the latter gained more income from selling fish. This indicates the higher relative importance of aquaculture in terms of improving access to nutritious food for households living in the food-insecure CDZ than for households in AD, where aquaculture is more commercially oriented.

Farmers gained a higher production (10,875 kg/ha and 5182 kg/ha equivalents; 117 kg/household (hh) and 8.3 kg/hh and income (12,895 USD/ha and 8383 USD/ha equivalents; 128 USD/hh and 13.4 USD/hh) from monoculture of pangasius (*Pangasius hypophthalmus*) and nile tilapia (*Oreochromis niloticus*) in the AD and CDZ respectively. However, the gross margin (1134 USD/ha and 3433 USD/ha) and benefit-cost ratio (1.1 and 2.2) from these species were lower than for other selected treatments. In terms of returns on investment silver barb (*Barbonymus gonionotus*) (1.9) and tilapia (2.2) proved to be the most profitable species in the AD and CDZ respectively. Rohu (*Labeo rohita*) monoculture showed similar results in production and gross margin to tilapia, however it could prove to be more successful than other species due to local fish preferences. In general, rohu in monoculture was the treatment that performed the best in terms of securing the highest gross margin. It was concluded that significant potential exists to develop small-scale aquaculture systems that can improve income and nutrition of all types of producers from both regions. Reference is made to the potential impacts of such changes on households if these systems and species were adopted more widely in Myanmar.

1. Introduction

Aquaculture production is growing in response to the high demand for fish globally, now becoming the fastest growing food production sector globally. Developing countries in Asia contribute > 80% of total aquaculture production to the world's food system. Aquaculture systems in Asia are predominately small-scale and family-owned, managed and operated (De Silva and Davy, 2010). Even if it is evident that contribution of small-scale aquaculture (SSA) in most developing countries is significant, SSA is however often not encouraged and overlooked in the government's development strategies in Myanmar (Belton et al., 2015).

Myanmar, a country of 53.26 million people in 2017, has 653,290 km^2 land area including extensive water resources in many parts of the country. Aquaculture production in Myanmar has grown at a rate of around 9% per year since 2004, driven by an increase in demand, production and associated income. Fish production has increased significantly in Myanmar over the last decade, due to an increase in farmed area as well as productivity improvements (Belton et al., 2015). There is a positive relation between household income and consumption of farmed fish in Myanmar with better off households eating more fish of aquaculture origin in urban areas while capture fishery products are more important in rural zones.

Processed fish products amount to 34% of fish consumed in the country whereas fresh fish from freshwater capture fisheries 27%, aquaculture 21% and marine capture fisheries 18% (So-Jung et al., 2018). Hence aquaculture plays an important and increasing role in fish for consumption in Myanmar, yet still below fish of capture origin. The scenario in Myanmar is different from neighboring Bangladesh and Thailand, where farmed fish represents 55% and 80% of domestic fish consumption respectively (Belton et al., 2015). Within the aquaculture sector, 99% of the production comes from inland waters (FAO FIGIS,

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2016; Joffre and Htin, 2017). One of the most striking features of aquaculture in Myanmar is the apparent absence of a vibrant small-scale aquaculture sub-sector.

It is evident, based on experience elsewhere, that a key benefit of aquaculture is the ability to provide a buffer for poorer households in the low income and food-deficit periods in a typical year, satisfying not only their immediate food needs (e.g. fish) but it also eases seasonal cash shortages (Béné, 2009; Belton et al., 2012; Karim et al., 2017). Moreover, fish raised in ponds may be considered as a more easily liquefiable asset, which can be sold to acquire income, similar to the demonstrated role of livestock within smallholder systems (Helgeson et al., 2013; Little and Edwards, 2003). Farmers with productive ponds can produce fish surplus to subsistence requirements that can be marketed to the benefit of the broader community (Edwards and Demaine, 1997; Islam et al., 2004; Little and Bunting, 2005). At present, the scope to improve and extend the benefits from large to small-scale producers has yet to be fully explored and developed. This includes assessing how the benefits of aquaculture are shared between men and women and how aquaculture investments can promote women's economic participation and empowerment in agricultural production, management and poverty reduction.

In general, aquaculture has the potential to reduce poverty either directly or indirectly (Edwards, 1999; De Janvry and Sadoulet, 2002; Kassam, 2013; Rashid and Zhang, 2019), not only through establishing and strengthening food consumption linkages, but also through "income linkages" and "employment linkages" (Ahmed and Lorica, 2002; Belton et al., 2011; Belton et al., 2014). The positive impacts on poverty of aquaculture development in Bangladesh have frequently been challenged (Rashid et al., 2016) as the practice is intrinsically linked with access to land and other resources (Karim et al., 2011). However, studies suggest that many poorer people are benefiting from increased aquaculture production in a variety of ways (Faruque, 2007; Little et al., 2007). Reducing poverty through smallholder development remains compelling in low-income countries - where the majority of people live in rural areas, and agriculture remains the largest single source of employment (Otsuka et al., 2016a; Otsuka et al., 2016b; Hazell et al., 2007; Wiggins, 2009; Hazell et al., 2010; Wiggins et al., 2010).

Despite all of the apparent untapped potential benefits and abundant water resources, growth of the small-scale aquaculture sector in Myanmar has not been encouraged and has been restricted to some extent (FAO and NACA, 2003; Filipski and Belton, 2018). The actual number of smaller commercial farms in the country is higher than what is officially reported (Belton et al., 2015). There are also > 200,000 small 'backyard ponds' present in the Ayeyarwady Delta (AD). These ponds are on average smaller than 0.4 ha in size. These ponds are underutilized and not considered as ponds as per the Department of Fisheries statistics.[1] Small ponds, either self-owned or leased, are common assets among poorer households and are partly used for fish culture but also for a variety of other purposes including irrigation of vegetable patches (Karim, 2006; Karim et al., 2017; Little et al., 2007). It is evident from several studies that there is an inverse relationship between pond size and productivity (Belton et al., 2012; Karim, 2006). The relative contribution of small farms as compared to large farms on the growth of local non-farm economy seems to be higher resulting in significant impact on agriculture growth (Belton et al., 2012; Ellis and Biggs, 2001; Haggblade et al., 2007). However, the importance of small water bodies and ponds supporting livelihoods directly, through food consumed by the producer household, compared to indirectly, through generating cash, has remained largely unexplored in Myanmar.

Aquaculture is practiced in both freshwater and brackish water in a number of systems in Myanmar. The sector is dominated by pond-based commercial aquaculture. The farms are located in AD, close to Yangon city and are highly concentrated. Most of these farms are very large, accounting for more than half of the overall pond area in Myanmar. However, their scale of production varies widely (Belton et al., 2017; Filipski and Belton, 2018). The main farmed fish-producing region in Myanmar is the AD region, where 90% of total farmed fish production takes place, the rest being produced in CDZ and upper Myanmar (Belton et al., 2015; DoF, 2018; Johnstone et al., 2012). The main reasons why the sector is concentrated there is the 1989 aquaculture law, which promoted conversion of uncultured 'wasteland' to fish ponds and the proximity to the main market: Yangon with a metropolitan population of over 7 million. In the AD region aquaculture is dominated by large-scale, export-oriented farms, while it consists mostly of smaller units for national consumption in the Central Dry Zone (CDZ). Currently the production is dominated by carp ponds in freshwater areas (mainly *Labeo rohita*) and tiger shrimp (*Peneaus monodon*) in brackish water ponds.

Most of the aquaculture farms in Myanmar can be characterized as semi-intensive, meaning they use a mix of both naturally available feed (phyto- and zooplankton) as well as supplementary feed (e.g. rice bran, groundnut oil cake). The most commonly cultured species are rohu and other major Indian or Chinese carps. Annually 100,000 metric tons of fish is exported, of which 65% is rohu; other species include tilapia or catfish.

Participation and adoption in aquaculture are expected to increase family earnings through higher employment levels, which in turn lead to higher net incomes. It is evident that adoption-consumption linkages can be achieved via two different pathways: firstly, direct consumption of fish produced by the household, and secondly by bringing down market price for fish due to an increased abundance/supply of fish products in the local market (Ahmed and Lorica, 2002).

Insights into the role of small-scale aquaculture systems in the overall livelihoods of better-off and worse-off farming households and the importance of location is largely lacking. Information is also required for the production capacity of such aquaculture systems and their role as a source of food supply and income, although these are often associated. Comparative analyses with respect to location (AD and CDZ), level of income and aquaculture system are important because it is anticipated that the level of income and location are likely to affect households' level of adoption and adaptation of pond-dike systems. Further, the contribution of fish to household food and nutrition security primarily depends on the availability and access to critical inputs on the one hand, and cultural and personal preferences on the other. These factors are largely determined by location, and price (Beveridge et al., 2013; Chastre et al., 2007). It is well evident that the behavior of relatively better-off and worse-off small-scale farmers in developing countries is based on 'economic' incentives; however, factors such as location, production systems, supply, demand and marketing systems should also be considered (Edwards and Demaine, 1997).

Even if the trend of aquaculture in Myanmar is positive so far, the growth of this sector has been disproportionately influenced and constrained by several factors including existing land use policy, despite significant potential contribution of small-scale aquaculture to local and regional markets providing increased income and nutrition (Belton et al., 2015). In Myanmar, aquaculture development faces key constraints including a lack of a comprehensive information base on aquaculture, a lack of proven management approaches and technologies for the scaling-out of suitable innovations, a poorly developed domestic market, and most importantly unclear land tenure. These factors are major obstacles for equitable aquaculture development in Myanmar. It is noteworthy that aquaculture is considered a 'non-agricultural' land use, the conversion of any paddy land or other agriculture land into aquaculture ponds is forbidden (Joffre and Htin, 2017). Although aquaculture has a long tradition in Myanmar, the sector is not very well developed compared to neighboring countries and there is thus room for expansion (Belton et al., 2015).

In the above context, with funding support from the Livelihoods and Food Security Fund (LIFT), the Myanmar Fish Culture (MYFC) project of WorldFish has sought to better understand adoption of SSA in

[1] Law relating to Aquaculture (The State Law and Order Restoration Council Law No. 24/89), 7th September, 1989.

Myanmar and how different aquaculture investments can be sustained and promising innovations can grow to a scale. The particular focus of the project has been to seek to enable growth of the aquaculture sector in ways that can make significant differences to the income and nutritional status of poor and vulnerable households.

These communities are often constrained by their limited access to and control over land and water resources (ADB, 2005; Belton and Little, 2011; Lewis, 1997). Rather than promoting a 'one size-fits-all' approach, the project set out to devise and adapt aquaculture technologies and related enterprise options to match the existing physical and human asset base, social and economic contexts, and expectations of supported communities.

Participatory processes, such as Participatory Community Appraisal have been conducted at the onset of this study with a particular focus on both community and market demands. The project was the first of its kind to specifically target small-scale aquaculture, thereby actively engaging rural communities in Myanmar. This paper outlines the processes followed in identifying appropriate intervention options and planning and implementing activities. The key aim of this study includes assessing profitability of several fish species combinations promoted in diverse aquaculture systems in varied locations so as to make recommendations to small-scale fish farmers in Myanmar. It was hypothesized that household's aquaculture production efficiency depends on several factors including aquaculture management practices, household level of income and education, location, gender and types of water bodies.

This paper tries to analyze how the species mix and culture systems performed best in each of the studied regions (the AD and the CDZ) in terms of key outcome indicators of fish productivity, consumption and economic profitability.

2. Methodology

2.1. Data collection

A Participatory Community Appraisal (PCA) was conducted between February and April 2016 to gain a better understanding of the local context prior to setting up the trial engaging 648 farmers from four townships (Bogale, Dedaye, Mawlamyinegyun, Pyapon) in the AD and two townships (Meikhtila, Yinmarbin) in the CDZ (Fig. 1). This took place in 49 separate sessions with farmers using several tools including a resource map, a seasonal calendar of different livelihoods and fishing seasons, Venn diagram for stakeholder analysis, and selection of preferred species to be cultured. Participatory approaches have been adopted for promotion of certain technologies within the communities by the project, as conventional extension approaches have not always been successful in benefiting socially marginalized and extremely poor communities (Chambers, 1994; Campbell, 2001).

The research team developed a total of six aquaculture packages, three in each of the study locations, with combinations of fish species available in the respective locations. One of the small indigenous species (mola carplet, *Amblypharyngodon mola*) (SIS) was included as in one of the polyculture systems tested. The rest of the management practices (e.g. feeding and fertilization) embedded in the packages were the same in all cases. The packages were then shared with the participatory action research farmers who had the freedom to choose which one to adopt and test in their own aquaculture resources (pond, *chan myaung*,[2] or WISH[3] pond).

Farmers recorded data on pre-stocking and post-stocking activities in the record books provided. The research team collected data from the record books on a monthly basis between May 2016 and December 2017 and entered the records into a database in Microsoft Excel, which was later transferred to IBM SPSS Statistics v23 (IBM Corp. Released 2015. IBM SPSS Statistics for Windows, Version 23.0.) for analysis.

2.2. Data analysis

It is worth noting that farmers who were unable to harvest any fish (production = 0 kg) were omitted from the dataset used in the analysis. The assumption is that farmers with production = 0 kg have an income from fish culture equal to 0 USD, because they haven't harvested any fish. The final dataset used in the analysis included data recorded from 501 farmers in 2016 and 2017. However, the analyses were carried out using a subset of the database that included only those treatments with > 20 replicates in order to facilitate a statistically robust analysis. This resulted in 423 records included in the comparisons between treatments (Table 1).

After grouping, a Kruskal–Wallis test was conducted to determine if there were any differences between zones and between systems regarding the characteristics analyzed. The production and gross margin were assessed across the different technology packages, pond designs (*chan myaung*, pond, and WISH pond), and regions (AD and CDZ).

An ordinary-least-squares, forward, stepwise regression method was used to assess which factors contribute the most to the variability in production across different aquaculture systems. Stocking density (fingerlings/ha), supplementary feeding (kg/ha), survival rate (%), and culture period (days) were added to the regression model for production. Several dummy variables such as fertilizer application (pre-stocking), lime application (pre-stocking), fertilizer application (post-stocking), lime application (post-stocking), type of water body (pond, *chan myaung*, WISH pond), each of the culture species, labor (pre-stocking and post-stocking), and zone were added to the regression model. Regression was run a first time to calculate Mahalanobis' and Cook's distances. Records with a Mahalanobis' distance higher than $x = \chi 2(0.05 \text{ level, n predictors})$ and a Cook's distance higher than 1 were removed and the regression model was run again.

3. Results

3.1. Farmers' profile

The average age of farmers (person who manages fish pond) was 46.7 ± 0.5 years old, 84% of farmers were men and 16% of farmers were women. The average occupancy of the households was 4.9 ± 0.1 people. The households earned on average 2493 ± 121 USD year^{-1}. The main occupation for the majority of the farmers surveyed (65%) was rice farming, followed by wage labor (16% of farmers). Only 13% of farmers had a high school diploma or higher. Thirty per cent achieved a middle school education, 30% achieved a primary school education and 21% of the households surveyed had only informal education or none at all.

3.2. Analysis by aquaculture systems

Tilapia monoculture was by far the most popular treatment (97.8%) in WISH ponds (Table 2).The most common treatment in earthen ponds was rohu-mrigal culture (26.2%), followed by tilapia-Indian major carps (rohu and/or mrigal and mola) (16.7%), rohu monoculture (13.7%), and rohu-Indian major carps (mrigal and/or catla) (13.7%). Pangasius monoculture was the most common treatment in *chan myaung* (30%), followed by tilapia-Indian major carps (rohu and/or mrigal and mola) (29%), and silver barb monoculture (19%).

3.3. Characteristics of production systems

The average size of the water bodies differed significantly across

[2] Chan Myaung is the local name of irrigation channels. These channels (both freshwater and brackish water) crisscross the Ayeyarwady Delta, providing irrigation water for plants and trees grown on the embankments.

[3] The WISH (Water and Fish) ponds are small ponds dug into permeable soil and lined with a plastic tarpaulin sheet bought locally (Kabir et al., 2015)

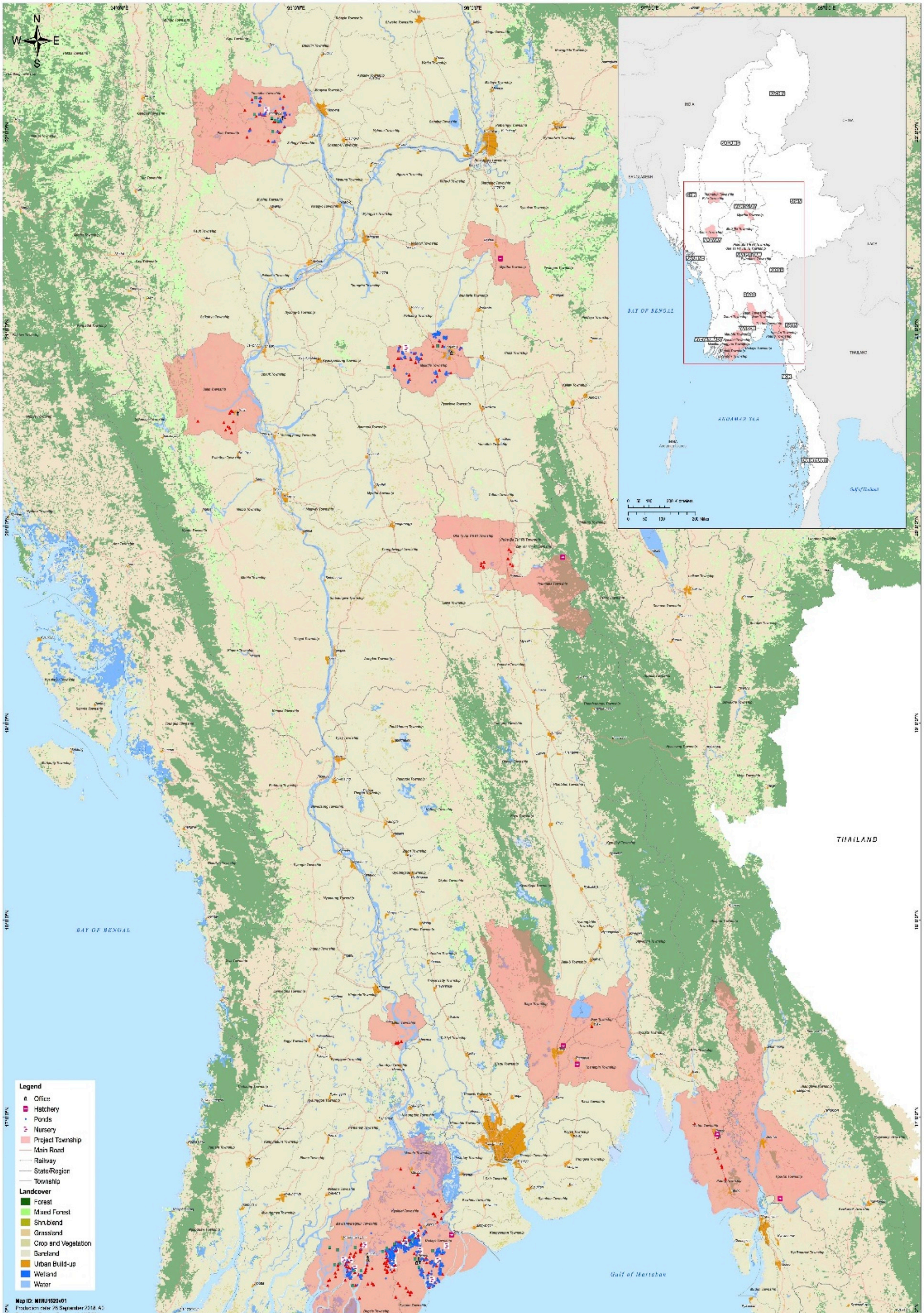

Fig. 1. Map of the study areas.

Table 1
Overview of selected treatments.

Treatments	Fish species	
	English name	Scientific name
T1	Tilapia	*Oreochromis niloticus*
T2	Rohu	*Labeo rohita*
T3	Rohu + (mrigal) + (catla)	*Labeo rohita* + (*Labeo mrigala*) + *Catla catla*
T4	Rohu + mrigal	*Labeo rohita* + *Cirrhinus cirrhinus*
T5	Pangasius	*Pangasius hypophthalmus*
T6	Pangasius + rohu	*Pangasius hypophthalmus* + *Labeo rohita*
T7	Mola + (tilapia) + (rohu) + mrigal	*Amblypharyngodon mola* + (*Oreochromis niloticus*) + (*Labeo rohita*) + *Cirrhinus cirrhinus*
T8	Silver Barb	*Barbonymus gonionotus*
T9	Silver Barb + rohu + mrigal	*Barbonymus gonionotus* + *Labeo rohita* + *Cirrhinus cirrhinus*

(Species between parentheses not present in all replicates.)

Table 2
Distribution of selected treatments across pond systems.

Treatments		T1		T2		T3		T4		T5		T6		T7		T8		T9		Total		Grand total
Zone		AD	CDZ	AD	CDZ	AD	CDZ	AD	CDZ	AD	CDZ	AD	CDZ	AD	CDZ	AD	CDZ	AD	CDZ	AD	CDZ	
Pond systems	*Chan myaung*	1	0	8	0	5	0	2	0	29	0	1	0	28	0	19	0	5	0	98	0	**98**
	Pond	1	4	13	19	5	27	54	7	23	0	22	1	40	0	1	2	12	4	171	64	**249**
	WISH Pond	0	88	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	90	**90**
Sub-total		**2**	**92**	**21**	**20**	**10**	**27**	**54**	**7**	**52**	**0**	**23**	**2**	**68**	**0**	**20**	**2**	**17**	**4**	**269**	**154**	**423**
Grand total		**94**		**41**		**37**		**61**		**52**		**25**		**68**		**22**		**21**		**423**		

Only treatments with n > 20 are shown in this table.

pond systems and between zones (Table 3). Earthen ponds are on average the largest (0.025 ha), followed by *chan myaung* (0.008 ha) and WISH ponds (0.001 ha). In the Ayeyarwady Delta, earthen pond owners had significantly ($p < .05$) larger ponds (0.029 ha) than earthen pond households in CDZ (0.018 ha). Stocking density was significantly different ($p < .05$) between all pond systems. The highest densities were observed in WISH ponds, followed by *chan myaung* and then earthen ponds. Feed Conversion Ratio (FCR) was significantly ($p < .01$) higher in *chan myaung* than in both earthen ponds and WISH ponds, at 6.9, 4.6, and 3.3 respectively. The survival rate was 76.7% in WISH ponds, which was higher ($p < .05$) than earthen ponds (61%) and *chan myaung* (47%).

3.4. Fish production and usage

Fish production was highest in *chan myaung* (6.8 metric tons/ha; 49.8 kg/hh), followed by WISH ponds (5.2 metric tons/ha; 7.5 kg/hh) and earthen ponds (4.5 metric tons/ha; 106 kg/hh) (Table 4). On average, the study households consumed 4.5 ± 0.4 kg (15% of total), gave away 2.1 ± 0.3 kg (4% of total), and sold 66.3 ± 5.8 kg (81% of total) of fish respectively. Pond farmers sold a significantly higher proportion of their harvest than did WISH pond farmers. Pond farmers in the CDZ sold significantly lower proportions of their harvest than farmers in AD. However, the total volume of fish harvested by AD farmers (including pond and *chan myaung* farmers) was higher ($p < .05$) than CDZ farmers.

In absolute values, pond farmers had higher harvests, so overall, they consumed, gave away, and sold higher quantities of fish as compared to *chan myaung* and WISH ponds. The quantities of fish being consumed in the household, given away, or sold at the market were also significantly higher for WISH ponds than for ponds. WISH pond households consumed around one third of the total amount of fish they harvested.

3.5. Economic characteristics

The average operational costs per unit area in *chan myaung* were USD 8112 USD/ha (54 USD/hh), which was significantly higher than earthen ponds (5303 USD/ha; 103 USD/hh) and WISH pond (5048 USD/ha; 8 USD/hh) (Table 5). Pre-stocking costs include lime, organic and inorganic fertilizer (urea and TSP), fuel, filling water, and pre-stocking labor. Post-stocking costs include lime, fertilizer, and labor.

Table 3
Pond characteristics by system and zone.

Parameters	*Chan myaung*	Pond			WISH Pond	Total (n = 475)
	AD (n = 112)	AD (n = 186)	CDZ (n = 85)	Total (n = 271)	CDZ (n = 92)	
Pond area (ha)	0.008 (0.004)^{a,c}	0.029 (0.035)*	0.018 (0.017)*	0.025 (0.03)^{a,b}	0.001 (0.002)^{b,c}	0.017 (0.025)
Stocking density (fingerlings/ha)	54,948 (38,014)^{a,c}	30,114 (23,050)	32,266 (25,501)	30,789 (23,819)^{a,b}	84,390 (16,546)^{b,c}	46,867 (33,921)
Survival rate (%)	53.3 (34.2)^{c}	60.6 (36.3)	62.6 (31.3)	61.2 (34.8)^{b}	76.7 (25.7)^{b,c}	62.3 (33.9)
FCR	6.9 (9.4)^{a,c}	3.9 (3.8)*	6.2 (9.9)*	4.6 (6.5)^{a,b}	3.3 (5.9)^{b,c}	4.9 (7.2)

Numbers in the parenthesis are standard deviation. Mean values followed by different superscript letters indicate significant difference ($P < .05$) based on Mann–Whitney U test.

Table 4
Destination of fish harvest by pond systems and zones.

Zone	*Chan myaung* (n = 112)				Pond (n = 271)			
	Cons (kg/ha)	Gift (kg/ha)	Sold (kg/ha)	Total (kg/ha)	Cons (kg/ha)	Gift (kg/ha)	Sold (kg/ha)	Total (kg/ha)
AD (n = 298)	792 ± 1380 (13%)	305 ± 688 (4%)	5809 ± 6474 (83%)	6897 ± 6976	415 ± 847 (10%^{b})	184 ± 649 (3% ^{b})	4575 ± 4050^{a} (87% ^{b})	5158 ± 4239
CDZ (n = 177)	–	–	–	–	209 ± 244* (11% ^{b})*	135 ± 536* (5% ^{b})*	2635 ± 2333*^{a} (84% ^{b})*	2979 ± 2376*
Total (n = 475)	792 ± 1380 (13%^{c})	305 ± 688 (4%^{c})	5809 ± 6474 (83%^{c})	6897 ± 6976	350 ± 725 (10%^{d})	169 ± 615 (4%^{d})	3967 ± 3707 (86%^{d})	4475 ± 3885

Zone	WISH (n = 92)				Total (n = 475)			
	Cons (kg/ha)	Gift (kg/ha)	Sold (kg/ha)	Total (kg/ha)	Cons (kg/ha)	Gift (kg/ha)	Sold (kg/ha)	Total (kg/ha)
AD (n = 298)	–	–	–	–	557 ± 1092	230 ± 665	5039 ± 5123	5812 ± 5486
CDZ (n = 177)	1386 ± 1724* (34%)*	137 ± 541* (3%)*	3726 ± 2777* (63%)*	5249 ± 2656*	821 ± 1383	136 ± 537	3202 ± 2624	4159 ± 2763
Total (n = 475)	1386 ± 1724 (34%^{c,d})	137 ± 541 (3%^{c,d})	3726 ± 2777 (63%^{c,d})	5249 ± 2656	655 ± 1214 (15%)	195 ± 622 (4%)	4355 ± 4448 (81%)	5196 ± 4725

Mean values followed by different superscript letters indicate significant difference ($P < .05$) based on Mann–Whitney U test.

Feed costs include commercial or farm-made pelleted feed, rice bran, and peanut oil cake. (See Table 6.)

Pre-stocking and post-stocking represented higher proportions of the total expenses in WISH ponds than in *chan myaung* or earthen pond households. Earthen pond farmers spent the least on fingerlings (1053 USD/ha), followed by *chan myaung* (1405 USD/ha), and WISH pond (1585 USD/ha). Overall, WISH pond farmers and farmers in the CDZ spent the most on pre-stocking expenses, while earthen pond and *chan myaung* farmers had considerably lower expenses prior to stocking. Feed costs (USD/ha) were the highest in *chan myaung* systems, and were significantly higher ($p < .05$) than in earthen ponds or WISH ponds.

Earthen pond farmers in the CDZ spent significantly ($p < .05$) less (63.5%) on feed than farmers in the Delta. Feed represented less than half (46.6%) of total costs in WISH pond farmers. The proportion of operational costs in WISH pond systems going to fingerlings was almost as high as feed, at 39.2%. Fingerlings represent around one fifth of total operational costs in *chan myaung* (21.1%) and earthen ponds (23.6%). WISH pond households spent around 40% of total costs on fish fingerlings. In *chan myaung* and earthen pond farmers, feed represents the bulk of the remaining costs, 73% and 70% respectively (Table 7). Feed costs represented less than half of total expenses in WISH pond systems (46.6%).

Post-stocking expenses (USD/ha) did not significantly ($p > .05$) differ between pond systems. Seed (1585 USD/ha, $p < .05$)), pre-stocking (619 USD/ha, $p < .05$), and post-stocking costs (289 USD/ha, $p > .05$) were higher for WISH pond farmers than for pond or *chan myaung* farmers, for each cost component (Table 5). There is no significant difference ($p > .05$) in post-stocking expenses between pond systems. Feed costs were significantly higher ($p < .05$) for *chan myaung* than for WISH ponds or earthen pond systems (6390 USD/ha, 5132 USD/ha, and 3974 USD/ha respectively).

The average income from fish production across all systems was 6918 USD/ha (86.8 USD/hh). Income was higher per unit area for WISH ponds (8651 USD/ha, 12.4 USD/hh) and *chan myaung* (8584 USD/ha, 61.0 USD/hh) than it was for earthen ponds (5608 USD/ha, 122.7 USD/hh). The gross margin between systems varied significantly ($p < .05$). WISH ponds achieved a gross margin (GM) (3603 USD/ha), on average, which is several times higher than in earthen ponds or *chan myaung*. Gross margin was relatively similar between *chan myaung* (526 USD/ha) and earthen ponds (325 USD/ha), albeit with a higher degree of variation in *chan myaung*. Farmers in the CDZ had significantly higher gross margins and Benefit-Cost Ratio (BCR) ($\frac{income}{expenses}$) than Delta farmers. WISH pond owners in the CDZ had significantly higher BCR than Delta farmers irrespective of which aquaculture system they utilized. The proportion of farmers who achieved positive gross margins was highest for WISH pond farmers (78%), followed by earthen ponds (53%). The proportion of positive earthen pond farmers was similar ($p > .05$) in the CDZ (55%) and in the AD (52%), while < 40% *chan myaung* farmers achieved a positive gross margin (Table 5).

3.6. Analysis by treatments

Tilapia farmers in the CDZ had on average smaller ponds, higher stocking densities, and higher survival rates than tilapia farmers in AD (Table 8). Rohu-Indian major carp polyculture farmers in the CDZ had significantly larger ponds than farmers in the AD while the opposite was true for rohu-mrigal culture. Stocking density was significantly different between zones for pangasius-rohu polyculture farmers (27,215 fingerlings/ha in the AD, 48,731 fingerlings/ha in the CDZ, $p < .05$). A similar trend in stocking density was also observed for silver barb polyculture farmers ($p < .05$). Tilapia (83,291 fingerlings/ha) and silver barb (79,335 fingerlings/ha) were stocked at the highest densities.

The average fish survival rate was around 65% while the lowest survival rate was observed in ponds stocked with silver barb-Indian

Table 5
Operational costs, production, and profitability by pond systems.

Particulars	*Chan myaung*	Pond			WISH Pond	Total		
	AD (n = 112)	AD (n = 186)	CDZ (n = 85)	Total (*n* = 271)	CDZ (n = 92)	AD (n = 298)	CDZ (n = 177)	Total (n = 475)
Capital cost (USD/ha)	396 (574)^{c}	264 (432)*	660 (1020)*	389 (697)^{b}	2264 (1401)^{b,c}	314 (493)*	1494 (1468)*	753 (1131)
Operational cost (USD/ha)	8112 (5427)^{a,c}	5656 (4198)*	4531 (3264)*	5303 (3958)^{a}	5048 (3119)^{c}	6579 (4838)*	4800 (3191)*	5916 (4380)
Fingerlings (USD/ha)	1405 (826)^{a,c}	1049 (949)	1061 (1075)	1053 (988)^{a,b}	1585 (330)^{b,c}	1183 (920)*	1333 (823)*	1239 (887)
Pre-stock (USD/ha)	176 (230)^{c}	155 (123)	299 (310)	200 (211)	619 (895)^{c}	163 (171)*	466 (697)*	276 (469)
Post-stock (USD/ha)	90 (235)	60 (197)	70 (341)	64 (250)	298 (1379)	71 (212)	189 (1025)	115 (649)
Feed cost (USD/ha)	6390 (4802)^{a,c}	4374 (3563)*	3100 (2420)*	3974 (3297)^{a,b}	2547 (2277)^{b,c}	5132 (4181)*	2812 (2357)*	4267 (3778)
Income (USD/ha)	8624 (9035)^{a,c}	5835 (4617)	5164 (3983)	5625 (4432)^{a,b}	8651 (4862)^{b,c}	6884 (6754)	6976 (4780)	6918 (6088)
Gross margin (USD/ha)	526 (7741)^{a,c}	184 (4263)	633 (4081)	325 (4205)^{a,b}	3603 (5723)^{b,c}	312 (5809)*	2177 (5206)*	1007 (5659)
BCR	1.18 (1.2)^{a,c}	1.2 (0.8)	1.4 (1.0)	1.23 (0.9)^{a,b}	2.2 (1.4)^{b,c}	1.2 (1)*	1.8 (1.3)*	1.4 (1.1)
% pos. Gross margin	39.3%	52.2%	55.3%	53.1%	78.3%	47.3%	67.2%	54.7%

Numbers in the parenthesis are standard deviation. Mean values followed by different superscript letters indicate significant difference ($P < .05$) based on Mann–Whitney *U* test.

major carp polyculture (22.6%) in the CDZ and the highest was in rohu-mrigal (81.9%) ponds in the AD. Rohu farmers in the AD had a higher FCR than in the CDZ. Pangasius-rohu culture in the AD had the lowest FCR (2.0), and FCR was the highest in rohu-mrigal culture in the CDZ (15.3). Significant differences for FCR were observed between the AD and CDZ for rohu monoculture (2.6 and 5.4, $p < .05$) and rohu-mrigal culture (4.0 and 15.3, $p < .05$) respectively.

3.7. Fish production and usages

The overall amount of fish harvested was significantly higher ($P < .05$) in the AD (5812 kg/ha and 101 kg/hh) than the CDZ (4159 kg/ha and 27.6 kg/hh). The highest yields are achieved in pangasius monoculture (11.5 metric tons/ha equivalent) and pangasius-rohu culture (9.6 metric tons/ha) in the AD. For most treatments, reported yields were higher in the AD compared to the CDZ, although the differences were only significant ($p < .05$) for rohu-Indian major carps and rohu-pangasius.

Rohu-Indian major carp polyculture farmers in the AD sold 100% of their harvest, which is significantly different from farmers in the CDZ (Table 9). On the contrary, CDZ farmers consumed or gave away a larger proportion of their harvest as compared to AD farmers. Pangasius-rohu farmers sold a significantly higher amount of fish in the AD than their counterparts in the CDZ.

3.8. Economic characteristics

Overall, no significant differences ($p > .05$) were found for post-stocking expenses between treatments or zones. Pre-stocking costs were higher in tilapia culture than in other treatments (Table 10). Seed costs were highest for pangasius and tilapia, 2102 USD/ha and 1541 USD/ha respectively. Tilapia had the highest expenditure in terms of pre-stocking expenses (591 USD/ha), followed by rohu-pangasius farmers (268 USD/ha). Tilapia farmers also had the highest post-stocking expenses of all treatments (285 USD/ha). (See Tables 11 and 12.)

Feed costs represent between around 60–80% of the total costs in most treatments. Feed costs were by far the highest in pangasius monoculture (9247 USD/ha). The lowest proportions of feed costs were observed in tilapia monoculture and pangasius-rohu culture, at 46.7% and 33.1% respectively in the CDZ. The proportion of feed as part of the total costs was significantly higher ($p < .05$) in both treatments in the Delta, at 78% and 72.9% respectively. Tilapia farmers located in the AD spent significantly more on feed compared to farmers in the CDZ, but when comparing absolute values, the difference is not significant.

The difference in the proportion of the total expenses related to fingerlings was not statistically significant between regions. Rohu farmers in the CDZ spent proportionately more on fingerlings and pre-stocking expenses, but less on feed. In absolute terms, the difference in expenses for seed is not statistically significant. The proportion of feed costs is significantly higher in the AD compared to the CDZ, for rohu-polyculture farmers, as CDZ farmers had higher pre and post-stocking expenses (fertilizer, lime, labour) than AD farmers, so the proportion of feed is lower.

Farmers culturing pangasius in monoculture systems achieved the highest incomes (12,895 USD/ha). Tilapia monoculture, rohu monoculture, and pangasius-rohu polyculture farmers gained similar incomes

Table 6
Operational costs, production, and profitability by pond systems (at household level).

Particulars	*Chan myaung*	Pond			WISH Pond	Total		
	AD (n = 112)	AD (n = 186)	CDZ (n = 85)	Total (*n* = 271)	CDZ (n = 92)	AD (*n* = 298)	CDZ (n = 177)	Total (n = 475)
Capital costs (USD/hh)	2.4 (3.6)^{a,c}	4.8 (7.5)	7.7 (8.5)	5.7 (7.9)^{a}	3.5 (3.7)^{c}	3.9 (6.4)	5.5 (6.8)	4.5 (6.6)
Operational cost (USD/hh)	54.1 (35.0)^{a,c}	119 (106)	68.2 (70.4)	103.3 (98.7)^{a,b}	7.8 (6.5)^{b,c}	94.8 (91.7)	36.8 (57.5)	73.2 (85.3)
Fingerlings (USD/hh)	10.1 (7.1)^{a,c}	25.7 (26.5)	15.5 (16.5)	22.5 (24.2)^{a,b}	2.4 (1.4)^{b,c}	19.8 (22.6)	8.7 (13.2)	15.7 (20.4)
Pre-stock (USD/hh)	1.4 (1.8)^{a,c}	4.4 (5.7)	4.6 (4.9)	4.5 (5.4)^{a,b}	0.9 (1.3)^{b,c}	3.3 (4.8)	2.7 (4.0)	3.1 (4.5)
Post-stock (USD/hh)	0.5 (1.3)	0.9 (2.8)	1.0 (5.8)	0.9 (4.0)^{b}	0.5 (2.0)^{b}	0.8 (2.4)	0.8 (4.3)	0.8 (3.2)
Feed cost (USD/hh)	41.8 (29.7)^{a,c}	88.0 (79.8)	47.1 (55.5)	75.2 (75.4)^{a,b}	4.0 (4.2)^{b,c}	70.6 (69.3)	24.7 (44.1)	53.5 (65.0)
Income (USD/hh)	61.0 (71.2)^{a,c}	139.5 (168.5)	86.1 (100.8)	122.7 (152.4)^{a,b}	12.4 (6.9)^{b,c}	110.0 (145.0)	47.8 (79.0)	86.8 (128.0)
Gross margin (USD/hh)	6.9 (58.8)^{a,c}	20.2 (103.7)	17.9 (80.7)	19.5 (97.0)^{a}	4.6 (9.2)^{c}	15.2 (89.7)	11.0 (56.5)	13.6 (78.9)
BCR	1.2 (1.2)^{a,c}	1.2 (0.8)	1.4 (1.0)	1.2 (0.9)^{a,b}	2.2 (1.4)^{b,c}	1.2 (1.0)	1.8 (1.3)	1.4 (1.1)
% pos. Gross margin	39.3%	52.2%	55.3%	53.1%	78.3%	47.3%	67.2%	54.7%

Mean values followed by different superscript letters indicate significant difference ($P < 0.05$) based on Kruskal-Wallis test. ^{abc}: by pond systems, *(pond, by zone)]

Table 7
Proportion of different categories of inputs as part of total operational cost by pond systems.

Costs (% of total operating costs)	*Chan myaung*	Pond			WISH Pond	Total (n = 475)
	AD (n = 112)	AD (n = 186)	CDZ (n = 85)	Total (n = 271)	CDZ (n = 92)	
Seed	21.1 (10.5)	22.3 (11.1)[b]	26.4 (13.4)[b]	23.6 (12.0)	39.2 (16.8)	26.0 (14.3)[a]
Pre-stocking	3.0 (3.4)	3.8 (3.8)[b]	9.0 (8.3)[b]	5.4 (6.1)	11.2 (13.6)	6.0 (8.2)
Post-stocking	0.7 (2.0)	0.9 (2.7)	1.2 (4.8)	1.0 (3.5)	2.9 (11.2)	1.3 (5.7)[a]
Feed	75.2 (12.2)	73.0 (12.9)[b]	63.5 (18.1)[b]	70.0 (15.3)	46.6 (17.8)	66.7 (18.2)[a]

Numbers in the parenthesis are standard deviation. Mean values followed by different superscript letters indicate significant difference ($P < .05$) based on Kruskal-Wallis test..
[a] By pond systems.
[b] Pond, by zone.

per unit area, at 8243 USD/ha, 8945 USD/ha, and 8859 USD/ha respectively. Tilapia and rohu monoculture have the highest gross margins (3333 USD/ha and 3548 USD/ha). This trend can also be observed in their respective benefit-cost ratios (2.1 and 1.8). Only three treatments had an average gross margin below zero, rohu-mrigal (−293 USD/ha), mola-tilapia-major Indian major carps (−317 USD/ha), and silver barb-rohu-mrigal (−3336 USD/ha). The average benefit-cost ratio for the all farmers is 1.4.

3.9. Analysis of production factors

The variability in production (kg/ha) in *chan myaung* systems is mainly linked to survival rate of the stocked fish and to a lesser extent linked with the total weight of supplementary feed applied during the culture period. Survival rate is also the main predictor for the variation in production in earthen pond systems. In both cases the coefficient for the variable survival rate is positively correlated with production, indicating a higher survival rate will lead to a higher production. The amount of supplementary feeding is also positively linked with production in both cases (Table 13).

Furthermore, in pond systems, initial stocking density is also positively related to production, albeit the coefficient is quite small and the increase in R^2 between the model not including stocking density and the model including stocking density was only 0.017 ($p < .005$). Lastly, in pond systems, a model including other variables was also statistically significant, but due to the low increase in R squared ($R^2 < 0.01$), these variables will not be discussed in depth.

The results for WISH pond systems are slightly different, with duration of the culture period (days) coming in as the predictor explaining the most variability in production. Duration is positively linked with production, a longer culture period resulted in higher production. Survival rate also plays a role in explaining the variation, although its explanatory power is limited ($R^2 = 0.035$, $p < .05$). However, the similar pattern was seen for expenses related to applying pre-stocking fertilizers in WISH pond systems ($R^2 = 0.035$, $p < .05$), however, the coefficient for this variable is negative, indicating an increase in pre-stocking fertilizers was linked with lower production.

4. Discussion

4.1. Analysis by aquaculture systems

4.1.1. Fish production

The level of fish production from *chan myaung* canals was very

Table 8
Pond characteristics by treatments and zones.

Treatment	Zone	Pond area (ha)	Stocking density (fingerlings/ha)	FCR	Survival rate (%)
T1 (*n* = 94)	AD (n = 2)	0.011 (0.01)*	42,354 (12,559)*	3.9 (2.4)	35.0 (0)*
	CDZ (n = 92)	0.002 (0.002)*	84,181 (19,726)*	2.9 (4.0)	77.4 (25)*
	Total	0.002 (0.003)	83,291 (20,476)	2.9 (4.0)	76.5 (26)
T2 (*n* = 41)	AD (*n* = 21)	0.015 (0.02)	24,932 (9754)	4.6 (5.2)	78.4 (25)
	CDZ (*n* = 20)	0.02 (0.02)	29,456 (20,457)	2.6 (2.0)	71.5 (25)
	Total	0.018 (0.02)	27,139 (15,862)	3.6 (4.1)	75.1 (25)
T3 (*n* = 37)	AD (*n* = 10)	0.017 (0.02)*	17,163 (345)	3.9 (2.5)	56.3 (15)
	CDZ (n = 27)	0.022 (0.01)*	19,322 (10,316)	5.0 (3.8)	72 (32)
	Total	0.021 (0.02)	18,739 (8822)	4.7 (3.5)	67.8 (29.3)
T4 (*n* = 63)	AD (*n* = 56)	0.035 (0.05)*	18,766 (9089)	4.0 (4.1)*	79.4 (45)
	CDZ (*n* = 7)	0.013 (0.02)*	37,235 (47,104)	17.2 (22.9)*	52.1 (35)
	Total	0.033 (0.05)	20,818 (17,951)	5.5 (9.1)	76.4 (44)
T5 (*n* = 52)	AD (n = 52)	0.012 (0.01)	36,456 (22,348)	3.7 (2.6)	82.0 (26)
T6 (*n* = 25)	AD (*n* = 23)	0.036 (0.03)*	27,215 (5685)*	2.0 (1.4)	62.5 (31)
	CDZ (n = 2)	0.007 (0.005)*	48,731 (26,438)*	5.6 (3.6)	35.4 (26)
	Total	0.033 (0.03)	28,937 (9707)	2.3 (1.8)	60.3 (31)
T7 (*n* = 68)	AD (*n* = 68)	0.022 (0.02)	49,117 (36,667)	5.7 (6.4)	28.2 (18)
T8 (*n* = 22)	AD (n = 20)	0.007 (0.005)	82,373 (28,619)	5.5 (5.7)	48.6 (26)
	CDZ (n = 2)	0.013 (0.01)	48,955 (31,193)	3.4 (2.9)	33.7 (18)
	Total	0.008 (0.006)	79,335 (29,734)	5.3 (5.5)	47.2 (25)
T9 (n = 21)	AD (n = 17)	0.011 (0.006)	41,917 (12,645)*	7.2 (5.3)	48.9 (28)
	CDZ (n = 4)	0.008 (0.003)	66,619 (12,645)*	7.1 (7.4)	22.6 (14)
	Total	0.01 (0.006)	46,622 (14,922)	7.1 (5.5)	43.9 (28)
Total (*n* = 423)		0.017 (0.03)	46,408 (33,105)	4.4 (5.5)	64.4 (34)

Mean values followed by different superscript letters indicate significant difference ($P < 0.05$) based on Kruskal-Wallis test. [abc]: by pond systems, *(pond, by zone)]

Table 9
Fish usage by treatments and zones.

Treatment	Zone	Consumption	Gift	Sold	Total
T1 (n = 94)	AD (n = 2)	1230 (1740) (28%)	0 (0) (0%)	2209 (340) (72%)	3439 (1399)
	CDZ (n = 92)	1378 (1729) (33%)	144 (541) (3%)	3660 (2661) (63%)	5182 (2578)
T2 (*n* = 44)	AD (n = 21)	793 (1268) (17%)	511 (1483) (6%)	5046 (5336) (77%)	6256 (5485)
	CDZ (n = 20)	174 (178) (5%)	3255 (1074) (7%)	4432 (3311) (88%)	4931 (3189)
T3 (n = 37)	AD (n = 10)	0 (0)* (0%)*	0 (0)* (0%)*	3773 (1214)* (100%)*	3672 (1234)*
	CDZ (n = 27)	240 (286)* (10%)*	103 (144)* (4%)*	2398 (2119)* (86%)*	2741 (2229)*
T4 (n = 63)	AD (n = 56)	501 (690) (19%)	146 (458) (4%)	2669 (3286) (77%)	3316 (3324)
	CDZ (n = 7)	230 (352) (15%)	30 (8) (4%)	2615 (3099) (81%)	3084 (3133)
T5 (n = 52)	AD (*n* = 52)	1115 (1648) (13%)	416 (618) (4%)	9343 (6461) (83%)	10,875 (6721)
T6 (*n* = 26)	AD (*n* = 23)	395 (712) (5%)	143 (442) (2%)	9009 (4314)* (93%)	9527 (3944)*
	CDZ (n = 2)	215 (304) (15%)	0 (0) (0%)	962 (61)* (85%)	1177 (365)*
T7 (*n* = 74)	AD (n = 68)	75 (185) (4%)	128 (513) (3%)	3334 (4598) (93%)	3528 (4643)
T8 (n = 22)	AD (*n* = 20)	1253 (1613) (20%)	410 (929) (4%)	4746 (3550) (76%)	6409 (4671)
	CDZ (n = 2)	502 (264) (28%)	23 (33) (1%)	1389 (502) (71%)	1914 (214)
T9 (n = 21)	AD (n = 17)	773 (1290) (16%)	256 (728) (7%)	2966 (2273) (77%)	3995 (3100)
	CDZ (n = 4)	365 (268) (25%)	0 (0) (0%)	1337 (932) (75%)	1702 (1129)
Total (n = 423)		706 (1263) (16%)	208 (651) (4%)	4451 (4563) (80%)	5355 (4810)

Mean values followed by different superscript letters indicate significant difference (P < 0.05) based on Kruskal-Wallis test. [abc]: by pond systems, *(pond, by zone)]

similar to earthen ponds and WISH ponds, indicating that it presents a viable option to establish or diversify freshwater aquaculture in the AD region. Typically, fish culture in the Delta has higher production levels than similar operations in the CDZ. This trend was also apparent in our study (DoF, 2018).

Most cultured fish species fetch a reasonably high price in wet markets in the AD (USD 1.11/kg), and even higher prices in the CDZ (USD 1.55/kg). Fish is scarce due to the limited availability of productive water bodies and current production is unable to meet the increasing demand. Above-ground water resources are not common in the Central Dry Zone (approximately 2% of land cover) (Bann et al., 2017), therefore establishing WISH ponds and/or similar technologies can serve a viable alternative, due to the lower land and water requirements. Production levels in WISH ponds were approximately three times lower in this study than in the one done by Islam et al. (2018), 5.3 and 18.8 metric tons/ha respectively. However, the duration of the production cycles differed (108 vs. 155 days respectively).

The low operating costs (7.8 USD/hh) of this system make it accessible for poorer households to take up fish culture. WISH ponds operating in this study were less intensively cultured than in the study conducted by Kwasek et al. (2015). The results obtained from the current study suggest that less intensively cultured WISH ponds are more beneficial in terms of cost-benefit. However, this comes with a reduction, in absolute terms, of the quantity of fish available for sale or for household consumption. Survival rate in WISH ponds (77%) was similar to that obtained (76%) by Islam et al. (2018), but lower than what was reported (89%) by Kwasek et al. (2015). In many cases the low survival rate was due to fish mortality shortly after stocking due to stress resulting from long travel times, as there was no hatchery close to the study sites.

4.1.2. Level of profitability

Higher operational costs in *chan myaung* were mainly due to higher feeding costs compared to pond and WISH ponds. One of the reasons for the high feed costs in *chan myaung* is that around one third of *chan myaung* farmers stocked pangasius, which consumed larger quantities of supplementary feed than major Indian major carp species (Haque, 2009; Ali et al., 2013; Mantingh and Dung, 2008). Earthen ponds and WISH ponds had no significant differences in overall operational costs. Feed costs (USD/ha) were significantly higher in earthen ponds, due to the higher absolute number of fish present in earthen ponds compared to WISH ponds. Feed-to-harvested-biomass ratio was highest in *chan myaung* (6.9). This could be linked with the fact that these systems are often lined by trees, thereby shading large areas of the water body, which might have in turn decreased primary productivity. Eventually fish (other than carps) stocked in *chan myaung* largely depended on supplementary feed. Alternatively, the high mortality rate in *chan myaung* could also explain the high ratio for feed-to-harvested-biomass. Further analysis on primary productivity in *chan myaung* and its contribution to fish diets is warranted.

Given the restrictions on the conversion of land to aquaculture ponds (maximum size for which a LUC (Land Use Certificate, Form 7) is not necessary is 116 m^2 (1250 sq. ft.), *chan myaung* and WISH ponds might be a good entry into fish farming due to the lower capital investment required to initiate canal or WISH pond culture compared to earthen ponds. Earthen ponds are usually larger in size and require larger investments in terms of pond digging and associated labor costs. The highest benefit-cost ratio was observed in WISH ponds (2.2 ± 1.4)

Table 10
Operational costs, production, and profitability by treatments.

Specifications	T1 (n = 94)	T2 (*n* = 41)	T3 (n = 37)	T4 (n = 63)	T5 (n = 52)	T6 (n = 25)	T7 (n = 68)	T8 (n = 22)	T9 (n = 21)	Total (*n* = 423)
Operation costs	4950 (3007)	5397 (3557)	4461 (2483)	4474 (4505)	11,761 (6838)	6596 (1547)	4641 (3008)	6144 (3689)	6962 (4205)	5927 (4473)
Seed	1541 (383)	807 (478)	773 (335)	818 (1096)	2102 (1280)	1592 (564)	970 (572)	891 (330)	959 (331)	1213 (850)
Pre-stocking	591 (873)	243 (345)	242 (306)	85 (89)	199 (314)	268 (155)	250 (59)	105 (146)	151 (114)	282 (485)
Post-stocking	285 (1364)	110 (320)	122 (472)	33 (113)	182 (285)	86 (269)	4 (26)	0 (0)	132 (334)	124 (686)
Feed	2533 (2223)	4236 (3051)	3283 (2227)	3533 (3891)	9247 (5335)	4646 (1570)	3349 (2768)	5149 (3607)	5709 (4052)	4288 (38756)
Income	8283 (4296)	8945 (7447)	4542 (2878)	4243 (4042)	12,895 (8924)	8871 (4511)	4335 (5661)	7227 (5773)	4987 (4019)	7167 (6240)
Gross margin	3333 (5525)	3548 (5952)	122 (3264)	−231 (4594)	1134 (7453)	2275 (4499)	−295 (5630)	1083 (7676)	−1975 (4309)	1246 (5804)
BCR	2.1 (1.4)	1.8 (1.2)	1.3 (0.7)	1.2 (0.8)	1.1 (0.6)	1.4 (0.7)	1.1 (1.2)	1.8 (1.8)	0.8 (0.7)	1.5 (1.2)

Table 11
Operational costs by zones and treatments.

Treatment	Zone	Operation cost (USD/ha)	Seed (USD/ha)	Pre (USD/ha)	Post (USD/ha)	Feed (USD/ha)	Income (USD/ha)	GM (USD/ha)	BCR
T1 (n = 94)	AD (n = 2)	4936 (3193)	690 (98)*	146 (173)	0 (0)	4101 (3268)	3656 (2239)	−1280 (954)	0.8 (0.03)
	CDZ (n = 92)	4950 (3021)	1561 (365)*	601 (880)	291 (1379)	2498 (2208)	8383 (4280)	3433 (5542)	2.2 (1.3)
T2 (n = 41)	AD (n = 21)	6331 (3621)*	731 (291)	157 (136)	215 (426)*	5227 (3237)	8508 (7943)	2177 (6938)*	1.4 (1.1)*
	CDZ (n = 20)	4417 (3296)*	887 (616)	333 (462)	0 (0)*	3196 (2518)	9404 (7064)	4987 (4434)*	2.3 (1.1)*
T3 (n = 37)	AD (n = 10)	5202 (2341)	724 (80)	51 (10)*	5 (16)	4269 (2302)	4318 (1402)	−730 (2906)	1.1 (0.7)
	CDZ (n = 27)	4187 (2520)	791 (390)	313 (332)*	165 (548)	2918 (2126)	4625 (3280)	438 (3382)	1.3 (0.8)
T4 (n = 63)	AD (n = 56)	4010 (3841)*	667 (303)*	65 (74)*	37 (119)	3235 (3737)*	4058 (3835)	48 (4198)	1.2 (0.8)
	CDZ (n = 7)	8186 (7510)*	2030 (3107)*	242 (0)*	0 (0)	5914 (4583)*	5723 (5577)	−2464 (7067)	1.0 (1.0)
T5 (n = 52)	AD (n = 52)	11,761 (6389)	2102 (1280)	199 (315)	182 (285)	9247 (5335)	12,895 (8924)	1134 (7453)	1.1 (0.6)
T6 (n = 25)	AD (n = 23)	6697 (1386)	1513 (366)	233 (78)*	38 (113)	4909 (1330)*	9452 (4214)*	2755 (4275)	1.5 (0.7)
	CDZ (n = 2)	5427 (3490)	2498 (1700)	673 (291)*	636 (895)	1620 (604)*	2179 (677)*	−3248 (4166)	0.6 (0.5)
T7 (n = 68)	AD (n = 68)	4641 (3008)	970 (572)	250 (60)	4 (26)	3349 (2768)	4335 (5661)	−295 (5630)	1.1 (1.2)
T8 (n = 22)	AD (n = 20)	6506 (3656)	914 (317)	90 (144)	0 (0)	5502 (3586)	7595 (5938)	1089 (8054)	1.7 (1.8)
	CDZ (n = 2)	2529 (1751)	664 (516)	246 (7)	0 (0)	1619 (1228)	3548 (507)	1018 (2258)	1.9 (1.5)
T9 (n = 21)	AD (n = 17)	7631 (4310)	908 (343)	130 (117)	156 (368)	6423 (7497)*	5419 (4281)	−2211 (4556)	0.8 (0.7)
	CDZ (n = 4)	4121 (2353)	1180 (199)	242 (0)	27 (46)	2673 (2296)*	3151 (2091)	−970 (3376)	0.9 (0.6)

Mean values followed by different superscript letters indicate significant difference (P < 0.05) based on Kruskal-Wallis test. [abc]: by pond systems, *(pond, by zone)]

Table 12
proportion of different categories of inputs as part of total cost for selected treatments, by zones.

Treatment	Zone	Seed (%)	Pre (%)	Post (%)	Feed (%)
T1 (n = 94)	AD (n = 2)	16.9 (8.9)	5.2 (6.9)	0 (0)	78.0 (15.8)*
	CDZ (n = 92)	39.1 (16.9)	11.5 (13.8)	2.7 (11.1)	46.7 (18.6)*
T2 (n = 41)	AD (n = 21)	13.5 (5.6)*	3.4 (3.7)*	2.7 (5.4)*	80.4 (9.7)*
	CDZ (n = 20)	26.1 (14.1)*	8.8 (9.9)*	0 (0)*	65.1 (20.4)*
T3 (n = 37)	AD (n = 10)	17.4 (8.5)	1.2 (0.7)*	0.1 (0.2)	81.3 (9.1)*
	CDZ (n = 27)	23.5 (11.4)	8.9 (5)*	3.1 (7.7)	64.6 (15.3)*
T4 (n = 63)	AD (n = 56)	23.2 (10.7)	2.1 (2.1)*	1.1 (3.2)	73.6 (11.3)
	CDZ (n = 7)	19.8 (9.6)	4.6 (2.6)*	0 (0)	75.5 (9.3)
T5 (n = 52)	AD (n = 52)	20.0 (7.2)	1.6 (1.9)	1.2 (1.8)	77.2 (6.8)
T6 (n = 25)	AD (n = 23)	23.5 (6.9)*	3.5 (1.2)*	0.5 (1.5)	72.5 (7.2)*
	CDZ (n = 2)	45.3 (2.2)*	13.5 (3.3)*	8.0 (11.3)	33.1 (10.2)*
T7 (n = 68)	AD (n = 68)	26.5 (12.7)	7.2 (4.2)	0.1 (0.6)	66.2 (15.4)
T8 (n = 22)	AD (n = 20)	16.7 (8.5)	2.0 (3.5)*	0 (0)	81.3 (9.8)*
	CDZ (n = 2)	25.2 (2.9)	12.7 (8.5)*	0 (0)	62.1 (5.6)*
T9 (n = 21)	AD (n = 17)	15.1 (9.4)*	2.7 (2.8)*	1.9 (3.7)	80.3 (10.8)*
	CDZ (n = 4)	35.0 (18.9)*	7.1 (3.1)*	0.4 (0.6)	57.5 (21.3)*

Mean values followed by different superscript letters indicate significant difference (P < 0.05) based on Kruskal-Wallis test. [abc]: by pond systems, *(pond, by zone)]

Table 13
Multiple regression model to estimate the impact of fertilizer application, stocking density, amount of supplementary feeding and other factors on production. Model summary *chan myaung*: $n = 96$, $R = 0.833$, R2 = 694,F (2,94) = 106.551; $p < .005$. Variables excluded from the model are not shown. Model summary pond: $N = 229$, $R = 0.839$, $R^2 = 0.704$, $F_{(3,226)} = 178.87$; $p < .005$. Model summary WISH Pond: $N = 89$, $R = 0.96$, $R^2 = 0.921$, $F_{(3,86)} = 335.721$; $p < .005$.

Pond systems	Independent variables	B	Std. Error	T-value	*P*-value
Chan myaung	Survival rate	95.79	14.19	6.75	0.00
	Feed total (kg/ha)	0.08	0.04	2.36	0.02
Pond	Survival rate	32.92	4.60	7.15	0.00
	Feed total (kg/ha)	0.11	0.02	5.35	0.00
	Initial stocking density (fingerlings/ha)	0.04	0.01	3.63	0.00
WISH Pond	Duration (days)	16.82	2.87	5.87	0.00
	Survival rate (%)	52.47	6.53	8.03	0.00
	Pre-stocking fertilizer (USD/ha)	−10.20	1.64	−6.21	0.00

Variables for which inclusion in the model for ponds was statistically significant ($p < .005$) but that are not shown in the table: Groundnut oil cake (if applied considered as 1, otherwise 0), pre-stocking fertilizer (USD/ha), pellet (if applied considered as 1, otherwise 0), zone (AD or CDZ). Variables for which inclusion in the model for WISH ponds was statistically significant ($p < .005$) but that are not shown in the table: initial stocking density (fingerlings/ha).

($p < .05$). Rural communities could initiate fish farming through investing in WISH ponds in areas with sufficient water resources available, which provides them with useful experience in managing fish culture all the while providing higher returns on investment than classical earthen ponds. After a few culture seasons, farmers might then make the transition to larger ponds and invest the money earned previously in WISH pond into intensifying or scaling up their operations.

WISH ponds had the lowest operational costs (USD/ha) and also recorded the highest incomes (USD/ha). Although *chan myaung* and WISH ponds recorded similar average production levels, income was significantly higher for WISH ponds. Fish prices are higher in the CDZ -where all WISH ponds are located- than in the AD -where all *chan myaung* are located- leading to higher incomes for WISH ponds. The highest mean gross margin in WISH ponds can be explained by relatively low operational costs compared to other systems, while having higher incomes on average. The economic efficiency of WISH ponds is also reflected in the BCR, which on average gave farmers a return of double (2.2 times) their initial investment. It is noteworthy, however, that only 39% *chan myaung* farmers achieved positive gross margins while it was 55% and 78% for ponds and WISH ponds, respectively.

4.2. Analysis by treatments

4.2.1. Fish production

The highest production levels were observed in pangasius and pangasius-rohu culture. This is consistent with the knowledge that pangasius growth rates are higher than for carp species and that they can also be stocked at higher densities, leading to higher production. The production levels in this study were in line (10–15 metric tons/ha) with those from other studies conducted in Bangladesh (Barman and Karim, 2007; Ali et al., 2018).

Most treatments did not show significant differences between zones, except for Rohu-Indian major carps, and pangasius-rohu, where production was significantly higher ($p < .05$) in AD than CDZ. This can indicate that environmental as well as ecological conditions did not significantly affect production in most treatments.

Tilapia production in WISH ponds was lower than what was reported by Islam et al. (2018), survival rates showed results similar to those obtained by Islam et al. (2018). A reason for the lower production levels than observed in Islam et al. (2018) is that farmers, limited by local fish seed availability, stocked smaller-sized fingerlings or even fish fry. This effectively reduced the culture period to a nursing stage rather than a grow-out phase, thereby affecting the resulting size and weight at the time of harvesting. The short culture periods observed for tilapia culture in WISH ponds could be due to the fact that smaller-sized fish are preferred locally, resulting in shorter culture periods for tilapia in CDZ than in AD.

Silver barb monoculture production in this study was approximately 2.5 times higher than reported by Hossain et al. (1998), although the culture period was slightly longer in this study (8 months compared to 6 months). The lower production levels observed in polyculture with rohu and mrigal might indicate competition between silver barb and rohu and mrigal, as noticed by Jena et al. (2007). Haque et al. (1998) noted an antagonistic relationship between silver barb and Indian major carps, although overall productivity was higher with addition of silver barb. Alternatively, as reported in Azim et al. (2004), addition of silver barb does not affect production performance of Indian major carps (rohu, mrigal and catla).

4.2.2. Level of profitability

The high operational costs in pangasius were mainly due to higher feeding costs, which were 1.5 times higher than for the treatment with the second highest expenditure (silver barb-rohu-mrigal). The proportion of feed in total operational costs was similar to other studies (77%, 75%, 75%) (Ahmed et al., 2010; Ali et al., 2018). Operational costs were several times higher than reported for pangasius culture in Bangladesh by Ahmed et al. (2010). Due to lower feeding costs, tilapia culture undertaken in WISH ponds, or rohu culture in *chan myaung* or earthen ponds, seems to be more affordable to households with limited financial capital.

Pangasius monoculture achieved higher incomes than polyculture with rohu, contrary to results from Bangladesh, reported by Islam et al. (2008). Fish yields were not significantly different between pangasius and pangasius-rohu polyculture, however, the pangasius monoculture farmers had a higher income from the significantly higher sales prices for pangasius. This is in contrast with prices in wet markets (pers. observation), where rohu is generally sold at higher prices than pangasius.

The average gross margin and benefit-cost ratio for pangasius culture that was obtained by farmers in our study was lower than reported by Ahmed et al., 2010, although most production variables (operational expenses and harvest) were similar. The difference in BCR could be explained by a higher FCR in our study than what was reported by Ahmed et al. (2010) and Ali et al. (2018), which were 3.7, 1.7, and 1.7, respectively. Adopting a more efficient feeding regime or gaining access to fish feed of a higher quality can reduce the FCR in the future, having a positive effect on gross margin and BCR. The cost of fingerlings was higher in our study compared to Ahmed and Ali, also contributing to higher overall operational costs. A higher initial investment on the key inputs (fish fingerlings) diminishes returns on production, or requires a higher proportion of harvest to be sold just to recover the initial outlay.

Of all treatments tested in the CDZ, tilapia monoculture obtained the highest production and incomes than for other treatments, resulting in higher income compared to other treatments, given that prices (USD/kg) are roughly similar for all fish species. Although total operational costs for tilapia were higher than most treatments, a higher income than in other treatments resulted in a higher gross margin for tilapia culture.

Rohu monoculture achieved the highest gross margins of all treatments tested in this study. Rohu culture in the CDZ had the single highest gross margin of all treatments from both zones. The lower gross margins recorded for rohu culture in the AD could be attributed to the fact that fish in the AD fetches a lower price than in the CDZ. All but two treatments (rohu-mrigal and pangasius-rohu) showed higher gross margins in the CDZ than in the AD. This suggests that fish farming might be more lucrative, albeit more challenging operation in the CDZ due to the limited availability of high-quality water sources. This does however add more relative importance to the cultured fish, as there are fewer wild fish available in this area.

The lowest gross margins were observed in silver barb-Indian major carps. Silver barb monoculture had the highest BCR in the AD, although pangasius monoculture reported higher incomes, feeding expenses were also higher. This is due to the fact that although operational costs are quite high, silver barb monoculture also reported higher incomes than most of the other treatments.

4.3. Inter-household fish consumption patterns

Increasing production levels and associated availability of fish in the Central Dry Zone could ultimately benefit the poorest households through strengthening ‘indirect consumption linkages’ (Toufique and Belton, 2014). It is noteworthy that food insecurity is high in the CDZ (18.5%, ADB Regional Technical Assistance Project RETA 8564), which explains the higher relative importance of fish from household ponds.

The proportion of fish consumed by the WISH pond farmers was around three times higher than earthen ponds. This might explain the higher demand and incidence of household consumption than was observed in the AD. The significantly higher volume of fish consumed by earthen pond owners in the AD than in the CDZ, although both groups consumed around 10% of the fish they produced. This corroborates the observations made by Johnstone et al. (2013) that aquaculture can contribute significantly to household nutrition.

The difference in proportion of fish destined for household use between the AD and the CDZ could indicate that farmers in the AD are more business-oriented than farmers in the CDZ due to a higher availability of fish in the AD and consequently easier access to fish resources in local wet markets (DoF, 2018). In the CDZ, where fish products are scarcer (Johnstone et al., 2013), having a source of fish available to the household has a higher importance than economic motives. This is reflected in the fact that both WISH pond farmers (located exclusively in the CDZ) and earthen pond farmers in the CDZ used a higher proportion of their harvest for household use (34% and 11% respectively, compared to 13% for *chan myaung* and 10% for AD earthen ponds), whereas *chan myaung* (exclusively in the AD) and pond farmers in the AD sold a higher proportion of their fish (83% and 87% respectively, compared to 63% for WISH ponds and 83% for CDZ earthen ponds). Even though production cycles in the CDZ were shorter, leading to smaller-sized fish, there seems to be a high enough market demand and no penalty on sales prices (Johnstone et al., 2013).

Mola polyculture production was more than double than reported by Kohinoor et al. (1998), albeit for a longer culture period. Detailed information about the contribution of mola to the total harvest biomass was not recorded in the farmer logbooks, only total harvest quantities were recorded. However, on average, households who stocked mola in their ponds were able to consume an amount between 6 kg and 9 kg per household in 2018, as documented through a separate study conducted more recently. It is noteworthy that 100 g of raw edible parts of mola can contain approximately 2680 RAE vitamin-A (FAO 2014). Small indigenous species, including mola, are rich in micro-nutrients, have the highest percentage of vitamin A, and a high content of calcium and iron (Rahman, 1989; Roos et al. 2002; Bogard et al., 2015a). Based on the study by Bogard et al. (2015b) in Bangladesh, *mola* with head and bones can contribute ≥25% of Recommended Nutrient Intake (RNI) of Vitamin A for Pregnant and Lactating Women (PLW) and for Infants (7–23 months old). This is based on the standard portion size of 50 g/day for PLW and 25 g/day for infants. Daily consumption of these species will be helpful in combatting malnutrition, which is currently of major concern in rural Myanmar.

No significant differences were found in fish usage pattern (home consumption, gifting, or selling) between most treatments across zones. The only exception was rohu-Indian major carp polyculture, where farmers in the AD sold 100% of their harvest, whereas farmers in the CDZ only sold around 86%. This could indicate that fish consumption pattern is adopted based on the quantity of fish available, rather than a regional preference for consuming one particular species of fish over other species.

4.4. Key factors associated with increased production

The results from the linear regression model showed that higher production was positively associated with fish survival rate. Higher survival rates indicate larger numbers of fish present in the pond and *chan myaung* systems, which as a result require more feed than ponds with a lower number of fish. Higher survival rates won't necessarily lead to higher production as there might be increased competition between the fish, reducing their individual growth rates. In this instance, given the fact that amount of feed used was positively correlated with survival rate, one can assume that growth rate was not negatively affected by the larger number of fish present in the pond as the carrying capacity in terms of food availability was artificially increased by bringing in external food sources. Therefore, ponds with higher survival rates ultimately recorded higher fish yields than ponds with low survival rates.

Consistent with results reported in Rahman et al. (2006a), higher stocking densities led to a higher yield in earthen pond systems. The effect of initial stocking density on yield is related to the point raised in the previous paragraph: a larger number of fish initially present in the pond can ultimately grow to a larger amount of fish of marketable size, given that growth rates are not restricted by natural levels of food availability.

The variance in production in WISH ponds was positively linked with culture period and survival rate and negatively linked with pre-stocking fertilizer use. Optimizing the grow-out period leaves more time for the stocked fish to reach higher body weights. Overuse of fertilizers prior to stocking may have affected water quality, increasing stress levels on the fish, resulting in a lower final harvest. More research is warranted to address what specific factors contributed to lower overall production linked with fertilizer use. Surprisingly, in WISH ponds, contrary to what would be expected from several studies (Boyd, 1998; Sahu et al., 2007; Kaur et al., 2015) that applied fertilizers prior to stocking fish showed a lower production than ponds that had not applied fertilizers prior to stocking.

5. Conclusion

The entry cost to small-scale aquaculture is seen to be relatively low as is shown by this study. Fish ponds can be constructed by modifying rice fields or unused backyard lands. Farm by-products such as rice bran or groundnut oil cake can be used as supplementary feed to raise fish in such water bodies. Production from small-scale aquaculture systems can be intensified through locally available organic and inorganic fertilizers. Direct benefits of fish farming mainly included a supply of highly nutritious food, and increased income through the sale of high-value produce. A higher proportion of fish harvest is destined for domestic use for CDZ farmers (both WISH pond and earthen pond), when compared to farmers in the AD. This indicates that the successful establishment of aquaculture operations potentially has a higher relative importance for households in the CDZ in terms of diet and nutrition than it has for households in the AD, where it is more commercially oriented. *Chan myaung* were tested as a novel way of culturing fish in rural villages. The production levels were similar to those achieved in classical earthen ponds and in WISH ponds and, therefore, *chan myaung* are considered a viable option for fish culture. From an economic point of view, however, *chan myaung* are less efficient so far. The highest operational costs were found in *chan myaung*, which were mainly due to high costs for feed. A closer look at feeding strategies may be warranted in order to improve the economic efficiency of *chan myaung* to allow for commercial development.

Pangasius monoculture and polyculture (with rohu) had the best performance in terms of production and gross margin in the AD. Production levels in pangasius ponds conform to what was reported by other studies looking at poor household production systems, although there is still room to intensify production even further. Rohu is a popular fish species due to its relatively lower price and good taste, which has a positive effect on marketability and subsequently on household income. The similar results obtained for tilapia and rohu monoculture in the CDZ in terms of gross margin and BCR highlight the fact that both are viable options for aquaculture operations. The choice of species rests mainly on the size of land available to the farmer, with locally available Nile tilapia mainly cultured in WISH ponds, which requires less land than rohu, which is mostly cultured in larger earthen ponds. Selecting smaller, fast-growing species might be more beneficial than culturing carp species, which overall have a relatively long culture period to reach optimal size (~600 g for carps, ~300 g for silver barb and tilapia).

In summary, pangasius was the most productive package, but associated operational cost were higher than for other treatments. Tilapia and rohu monoculture systems achieved lower production levels than pangasius, albeit at lower operational costs, making it more accessible for poorer households. Although production levels were higher in the AD than in the CDZ, gross margins for fish culture were higher in the CDZ for most treatments, highlighting the higher relative economic benefit on top of the food and nutrition security aspect.

Aquaculture provides a range of benefits to households not directly involved in fish culture, but rather through indirect linkages. Households can benefit from an increased supply of fish and fish-based products in local markets, which might drive prices down. Increased employment opportunities could be created along the fish farming value chain, both direct employment on farms as well as in associated services (feed, seed, inputs such as fertilizers).

Ethical statement

I hereby affirm that the content of this manuscript are original. Furthermore it has been neither published elsewhere fully or partially or any language nor submitted for publication (fully or partially) elsewhere simultaneously.

I also affirm that the all authors have seen and agreed to the submitted version of the paper and their inclusion of name(s) as co-author (s).

Author Contribution

Statement about authorship and the different roles for each author:

Manjurul Karim: conceptualization, writing-original draft, supervision, funding acquisition, project administration.

Kimio Leemans: writing- original draft, methodology, data curation, formal analysis.

Michael Akester: writing-review & editing.

Michael Phillips: writing-review & editing.

Declaration of Competing Interest

None.

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