



Sustainability impacts of ecosystem approaches to small-scale aquaculture in Bangladesh

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Abstract

This study explores the sustainability impacts of adopting an ecosystem approach in underutilized homestead ponds (ecoponds) operated by women in Bangladesh. Households with ecoponds have significantly higher fish productivity, fish diversity, and income generation potential compared to households with similar underutilized ponds. Furthermore, certain dimensions of women's empowerment are improved at the individual and household level (e.g., control of income and productive assets), without, however, addressing wider structural inequalities. Food security impacts are rather inconclusive, as despite the higher consumption of more diverse fish species among ecopond households, there is no significant effect on overall dietary diversity.

Keywords Food security · Women's empowerment · Rural livelihoods · Income · Fish productivity · Fish diversity

Introduction

The demand for animal protein (including fish) has been increasing globally in the past decades (Cao and Li 2013; Kastner et al. 2012; FAOSTAT 2020). Depending on the geographical context, different factors, such as population growth and changes in dietary preferences, have driven this increase (Alexander et al. 2015; Kastner et al. 2012; Weindl et al. 2017). However, this increase has been largely linked to negative environmental impacts. For example, the expansion and transformation of terrestrial livestock production systems have been linked to extensive land use change,

ecosystem degradation, greenhouse gases (GHG) emission, pollution, and biodiversity loss (IPBES 2019). The combined effects of increased fish demand with unplanned aquaculture and unregulated fishery practices have been linked to fisheries overexploitation, ecosystem degradation, and pollution (Amirkolaie, 2011; Merino et al. 2012; Henriksen et al. 2018).

Several studies have suggested that decreases in the demand and supply of some types of animal protein, especially meat, can have major environmental benefits (Hartmann and Siegrist 2017; Henschion et al. 2017). Yet, in some parts of the developing world, there is a real need to expand the supply and consumption of animal protein to improve household nutrition and enhance food security (Béné et al. 2015; Beveridge et al. 2013). However, the expansion of some conventional livestock systems is not always feasible or desirable due to various production constraints (e.g. land/water scarcity) and cultural reasons (e.g. religious sensibilities) (Nam et al. 2010; Weindl et al. 2017). In fact, the rapid current population increase and improvement in economic conditions could also catalyse a rapid increase in animal protein demand in many developing countries (Henschion et al. 2017).

Despite some challenges, aquaculture is a possible avenue to meet some of this increasing animal protein demand in a sustainable manner (Hua et al. 2019). Studies have pointed

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that in some developing contexts, small-scale aquaculture systems have a huge potential to provide animal protein in an environmentally sustainable, and socially and culturally appropriate manner (Ross et al. 2008; Subasinghe et al. 2009; Thilsted et al. 2016). For example, some small-scale aquaculture systems have been linked to various positive socioeconomic impacts linked to livelihoods (Ross et al. 2008; Toufique and Belton 2014), food security (Ahmed and Lorica 2002; Béné et al. 2016) and some level of women's empowerment (Farquhar et al. 2019; Choo and Williams 2014). However, such aquaculture systems face constraints related to access to knowledge, credit, or inputs (Henriksson et al. 2017; Cole et al. 2020), or the inclusive engagement in terms of gender, wealth, or age, among others (Diedrich et al. 2019; Harohau et al. 2020; Kruijssen et al. 2018).

Bangladesh is one of the developing countries where small-scale aquaculture already plays a major role for the livelihoods and food security of a large fraction of the population (Hernandez et al. 2018; Jahan et al. 2010; Siddiqua et al. 2017). Both public and private organizations have strongly promoted aquaculture in an attempt to meet fish demand. With an annual production of about 2.4 million tonnes of cultured fish, Bangladesh ranked in 2018 as the world's fifth-largest inland aquaculture producer (FAO 2020). In 2018–2019, aquaculture accounted for 56.76% of the total national fish production (for comparison, inland capture fisheries contributed 28.19%), reflecting a 134% increase compared to 2008–09 levels (1.06 million tonnes) (DoF 2019). Average aquaculture yields range varies between systems: from 4.96 t/ha for ponds, 1.50 t/ha seasonal waterbodies, 1.82 t/ha baors (oxbow lakes), and 0.99 t/ha for shrimp gher¹ (DoF 2019). Even though some of the aquaculture output is exported (73.1 thousand tonnes in 2018–2019), most is consumed nationally (DoF 2019).

When it comes to the main production approaches, aquaculture production systems in Bangladesh are mainly semi-intensive and intensive (Belton and Azad 2012; Hosain 2015). Inland ponds are the mainstay of Bangladesh's aquaculture sector, accounting for around 80% of the total aquaculture output and are presently dominated by carp (indigenous and exotic), pangasius, and tilapia species (DoF 2019). Roughly 4.27 million households (20% of the rural population) operate at least one homestead pond, which are typically small in size (0.08–0.1 ha on average). This small size reflects land scarcity, high construction costs, and the fact that the ponds have multiple domestic uses, such

as washing, bathing, and cooking (Belton and Azad 2012). Usually small homestead ponds cater to household food needs, but commercial production is increasing for some (or all) of a household's aquaculture output (Belton and Azad 2012; Choudhury et al. 2017).

The aquaculture sector has considerable socioeconomic impacts in the country, considering its scale and extent. For example, the sector contributes substantially to income generation and poverty alleviation (Azad et al. 2009; Siddiqua et al. 2017). Furthermore, it contributes to food and nutritional security, as 60% of the animal protein intake in the country is obtained from aquatic animals (FAO 2016; Toufique and Belton 2014). As a result, the average annual per capita fish consumption in Bangladesh is higher compared to the global average (FAO 2020). However, Bangladesh's aquaculture sector has also been linked with various sustainability challenges, such as the degradation and pollution of water bodies, low-value addition, and constraints in farmers' access to good-quality input (e.g. high-quality seed of improved fish strains, high-quality feed) (Ghose 2014; Nabi 2008). There are also major discrepancies between social groups in terms of fish consumption, with poorer families, women and children consuming less fish per capita than the national average (Beveridge et al. 2013; Mostafa et al. 2008).

Women play a significant role in Bangladesh's aquaculture sector. When it comes to employment, the official statistics report that 1.4 million of women (out of 17.8 million employed women) are occupied in the aquaculture and fisheries sectors (FAO 2017). However, other studies have estimated a much larger proportion of women engaged in certain aquaculture activities. For instance, women account for > 80% of the labor force in fish processing companies (Shamsuzzaman et al. 2017), and > 50% of casual laborers in fish drying sites (Belton et al. 2017). However, despite their large share of employment in the aquaculture sector, the actual benefits for women are questionable or not adequately assessed. For example, while the extensive employment of women in the fish industry is seen as a positive indication for women's empowerment (Gopal 2014), the fact remains that women are mostly employed in lower level jobs and their role remains largely underreported in national statistics (Ahmed et al. 2012; Halim and Ahmed 2006; Shelly and D'Costa 2001).

When it comes to homestead aquaculture production, women account for up to 22% of the total labor (Jahan et al. 2015). Indeed, it is estimated that approximately 43% of rural women dedicate some of their time to homestead aquaculture (Halim and Ahmed 2006). Thus, it has been perceived as a fertile ground to empower women. The research and development foci for women in the aquaculture–agricultural sector in Bangladesh have been largely confined to such homestead systems, which are perceived as a convenient domain that can “accommodate” women's mobility and

¹ Ghers in Bangladesh are traditional agriculture system consisting of modified rice fields use for fish farming where a pond is dug into the rice field and the dug out soil is used to create high, broad peripheral dykes around the pond for growing vegetables (Morgan et al. 2015; McDougall 2017).

access issues (Aregu et al. 2018; Choudhury et al. 2017; Farnworth et al. 2016). However, attaining women's empowerment through aquaculture innovations through homestead pond system has also been challenging, with most interventions enabling empowerment only at the welfare and access levels (Choo and Williams 2014). This has often left other key elements of empowerment, such as the control over pond or income, and the ability to make important life choices either unattained or with incremental changes (Choudhury et al. 2017). This has pointed towards the structural inequalities that gender norms and power relations present in rural Bangladesh. However, it has also shown that it is challenging to achieve all dimensions of women's empowerment simply through inclusion in homestead aquaculture innovations (Choudhury et al. 2017).

The sustainable intensification² of small-scale aquaculture systems in Bangladesh offers a huge opportunity for curbing some of the sector's negative environmental impacts, while enhancing socioeconomic benefits associated with pond productivity, food security, rural livelihoods, and women's empowerment (Azad et al. 2009; Belton and Thilsted 2014; Jahan et al. 2010, FAO 2010). As a result, various innovations have been geared towards improving the performance of small-scale aquaculture systems in the country (Jahan et al. 2015).

One promising innovation has been the ecopond model, which has sought to enhance fish production and pond productivity by empowering women to employ ecosystem approaches to aquaculture in underutilized homestead ponds (WorldFish 2017). Ecosystem approaches to aquaculture encompass diverse strategies that consider ecosystem functions and services (and avoid compromising their sustained delivery), improving in the process human wellbeing and equity for all relevant stakeholders (Brugère et al. 2019; FAO 2010). In the ecoponds models, the ecosystem approach relates to the improvement of fish habitat through the use of readily available natural materials (e.g. aquatic vegetation, coconut leaves, bamboo tubes/branches), whose potential is further leveraged by the iterative training of women on how to develop, manage and effectively use the ponds and produced fish (WorldFish 2017). It was hypothesized that such "ecoponds" that combine ecosystem approaches to aquaculture in underutilized ponds, with capacity-building for women, can have multiple ripple positive impacts for

livelihoods, food security, and some dimensions of women's empowerment (refer to the Methodology for a delineation of the women's empowerment aspects of the ecoponds model).

The aim of this study is to assess through an interdisciplinary mixed-method approach the major sustainability impacts (and specific pathways to impact) of the "ecoponds" production model. The Methodology section outlines the (a) analytical framework and the pathways mediating ecoponds' impacts, (b) the women's empowerment aspects of the ecoponds model (c) study sites and groups, (d) data collection and analysis methods. The Results section highlights the impacts of ecoponds on fish productivity, household income, food security, and dimensions of women's empowerment, comparing different treatment groups (i.e. ecopond users) and their respective control groups. The Discussion section critically synthesizes the main findings and offers recommendations on how to further improve the sustainability performance of ecosystem approaches to small-scale aquaculture.

Methodology

Research approach

Ecoponds intervention

The ecoponds model is essentially a user-oriented sustainability solution. The model seeks to maximize in a cost-effective manner the potential of small and underutilized homestead ponds for women-led small-scale fish production, predominately for subsistence and secondarily for market selling (WorldFish 2017).

These ponds are smaller in size (250–500 m²) than average household ponds and are not originally destined for fish production but are often the remains of digging operations for housing, agriculture or infrastructure (e.g. ditches). The ponds can be seasonal (i.e. completely dry up during low-rainfall months) or perennial (i.e. hold water throughout the year). Even though some of these ponds are used for fish production using extensive management approaches, this is usually the exception, with the actual productivity being very low (usually < 500 kg/ha) (WorldFish 2017).

The ecopond approach was conceived during preliminary participatory action research with about 60 women and 60 ponds, in four communities located in two polders in Khulna District. This early work highlighted that readily available natural habitat elements, such as bamboo branches, roots, and aquatic vegetation, can offer a good shelter and source of natural food for many different fish species, and thus increase fish diversity and overall pond productivity (Kabir et al. 2015; WorldFish 2017). These preliminary observations suggested that this simple and affordable ecosystem

² Sustainable intensification seeks to increase aquaculture production, while limiting adverse environmental impacts (Henrikson et al. 2018; Ellis et al. 2016). For small-scale aquaculture and fisheries systems, studies have found that practices, such as improved harvest strategies, disease management, and waste reduction, among others, can increase production efficiency and help achieve sustainable intensification goals (Engle et al. 2017; Haque et al. 2016; Henriksson et al. 2018; Joffre et al. 2018).

approach to aquaculture can leverage the potential of underutilized ponds for small-scale fish production, providing in the process a secondary option for household-level food production and income generation. However, the preliminary observations also suggested that despite its potential for the active and meaningful engagement of women in small-scale aquaculture, training and capacity-building would be needed to both effectively implement the ecopond model and maximize its possible outcomes (see Conceptual Framework for more information about the expected outcomes).

To test at a larger scale, the potential of the ecoponds model, WorldFish facilitated the development of (a) women groups in rural communities, (b) training to instill leadership skills to some women farmers (i.e. lead farmers, see more details in next paragraph), and (c) learning centers to facilitate this learning process in an iterative manner (rather than one-off) (WorldFish 2017). In particular, following an initial training, the participating women could visit the training centers multiple times as per their needs, having ready access to extension personnel to receive assistance on ecopond development and management.

Central to the ecoponds model was the initial training of some women farmers in each intervention community from WorldFish personnel to instill them with leadership skills. Through this early training, these selected women assumed the role of lead farmers, enabling them in turn to provide training to other women farmers in their communities with the help of extension staff. This training consisted of a series of sessions focusing on technical, value chain and women's empowerment aspects (see Box S1 in Supplementary Material for more details in this training). This training reached a total of 297 lead farmer women across the study area. The underlying rationale was that the women lead farmers would act as a constant reference point of ecoponds information within their communities (Box S1, Supplementary Material). By virtue of being local women also involved in fish production in their own ecoponds, it was expected that the women lead farmers could provide more confidence to the other local women targeted by WorldFish in each community to seek information, which might not have been the case if they had to refer to men lead farmers or extension personnel external to the community.

The wider Ecoponds training activities reached 3377 women in the Khulna and Barguna districts (see next section), transforming 3750 underutilized homestead ponds to ecoponds adopting the management practices outlined above.

Conceptualizing women's role and empowerment in the Ecoponds intervention

Women have been the focus of the Ecoponds intervention, as they are the main caretakers of their households (and

thus responsible for nutrition). However, as mentioned in the Introduction, women are also largely excluded from aquaculture activities in larger ponds that have accounted for most aquaculture growth in Bangladesh. This is mainly because women lack access and control over inputs (e.g. capital, land) and therefore find it difficult to invest in more intensified production methods that could otherwise enhance fish productivity and production, as well as other aligned benefits. With men mostly controlling investment decisions in ponds, women in rural Bangladesh are usually unable to apply the knowledge obtained through aquaculture training to larger ponds (Choudhury et al. 2017; Farnworth et al. 2016; Morgan et al. 2015).

However, due to their small size, the ponds used as 'ecoponds' are mostly underutilized or not utilized at all for fish production in most households (see "Ecoponds intervention"). As men in rural Bangladesh tend to normally consider these ponds of lower (or even no) importance for fish production, they are more willing to consider fish production in such ponds led by women household members. However, it was expected that using ecoponds productively over long periods of time would allow a larger supply of fish for household consumption, with women gradually building up confidence and obtaining the control of these ponds. Overall, it was expected that empowering women in this way to engage meaningfully in fish production would encourage a more proactive role over household decision-making (including food-purchasing decisions), having further possible ripple impacts for food security.

When delineating the above, this study recognizes the dual role of the ecopond model for women's empowerment,³ as both a mechanism to enhance sustainability and an outcome impact of the specific intervention (McDougall 2017; Lau 2020; Lawless et al. 2021).

First, women's empowerment is seen as an instrumental value acting as a mechanism/pathway to achieve outcomes that improve household income and enhance food security. Second, women's empowerment is seen as one of the impacts of the ecoponds model, along with impacts, such as improved yields, income generation and food security. In this sense, women's empowerment is seen as an intrinsic value seeking gender equality as a major sustainability benefit on its own right. To assess women's empowerment as an impact/outcome of the ecoponds intervention, the study adapts IFPRI's Women's Empowerment in Agriculture Index (WEAI) tool in the household survey (Stage 2) and the Ladder of Power and Freedom tool developed by GENNOVATE

³ We adopt Naila Kabeer's definition of empowerment, which is "the expansion of people's ability to make strategic life choices in a context where this ability was previously denied to them" (Kabeer, 1999: 437). Strategic life choices are multidimensional and influenced by structures and norms, which this project did not address.

in the Focus Group Discussions (FGDs) (Stage 3) (see “Data Collection” and “Data Analysis for more information).

Conceptual framework

This study adopts a sustainability science lens to elicit the impacts (and related pathways) of the ecoponds model, adopting many of the paradigm’s central elements, such as the strong linkage between social and ecological systems, a user-oriented perspective, and an interdisciplinary approach, that utilizes different sources of knowledge and viewpoints (Komiya and Takeuchi 2006; Lang et al. 2012; Kates 2011).

Figure S1 systematizes the expected impacts and impact pathways from the ecoponds model. In particular, the ecopond model hypothesizes two pathways where ecopond development and women’s access and control over ecoponds lead to improved food security. First, the adoption of ecosystem approaches to aquaculture can boost fish species diversity and pond productivity. Combined with women’s capacity-building schemes to manage these ponds, it was expected that it would allow these sources to become a stable fish source, thus increasing household food availability, stability, and reducing fish purchases (and associated expenses). Second, by selling excess fish output from ecoponds (if any) could provide income, which combined with women’s control over this income, it would allow the purchase of other types of food, increasing thus dietary diversity.

Figure S2 in the supplementary material illustrates the three-stage process we followed to assess ecopond impacts. In summary, Stage 1 entails a rapid baseline household survey to design the impact assessment protocol. Stage 2 entails a comprehensive household survey to assess quantitatively the impacts across the pathways described above. Stage 3 was designed and undertaken after the analysis of the household survey results and entails a series of focus group discussions (FGDs) with selected respondents to identify why some of the expected impacts and pathways did not manifest as expected.

Study sites and groups

Two intervention and two control areas were selected to assess the impacts of the ecoponds model. In terms of groups, we survey households adopting the ecoponds model (i.e. intervention group) and households not adopting the ecoponds model (i.e. control group). However, as many households in rural Bangladesh engage in other aquaculture activities (see Introduction), larger aquaculture ponds are quite prevalent. For this reason, we study four distinct groups (Figure S3, Supplementary Material):

- (a) households that only have underutilized ponds and received the ecoponds training (ecoponds);
- (b) households that have underutilized ponds, as well as other pond and ghers, and received the ecoponds training (ecoponds +);
- (c) households that only have underutilized ponds but did not received the ecoponds training (control);
- (d) households that have underutilized ponds, as well as other pond and ghers, but did not receive the ecoponds training (control +).

Considering the relative ease of developing ecoponds, there is a high likelihood that households not receiving the ecoponds training, could become aware of and adopt some (or all) of the management practices through word of mouth or by observing neighbors, friends, and family. Such spillover effects are quite common in aquaculture and agricultural interventions, where knowledge dissemination is a major component (Dompheh et al. 2020; Miyata and Manatunge 2004; Lee et al. 2019). To decrease the likelihood of spillover effects, we selected control groups in areas that did not receive the intervention, but were at some distance, located in separate polders, and shared largely similar characteristics with the intervention areas (Table S1, Supplementary Material). In particular, intervention groups (i.e. ecoponds, ecoponds +) were collected from Polder 29 and Polder 43/1A, while control and control + groups from Polder 30 and Polder 43/2F (Figure S4, Supplementary Material).

Data collection

During Phase 1, we conducted a rapid baseline assessment (October 2018) in 300 randomly selected households that received the ecoponds training. Even though the results of this baseline survey are not reported in this paper, they helped us identify the possible impact pathways and relevant variables. Moreover, this baseline provided insights to design the final sampling protocol described below.

During Phase 2, we conducted a detailed household survey to assess the sustainability impacts of the ecoponds model. In total, 1328 households were randomly selected for the household survey, of which 666 households were located in Khulna district (Site 1) and 662 in Barguna district (Site 2) (Table S1, Supplementary Material). All groups were sampled randomly from lists that were developed prior to fieldwork, containing basic household information, such as the type and number of ponds. We focused relatively more on households that had only small underutilized ponds (i.e. ecopond and control groups) rather than households that had also other ponds (i.e. ecopond + and control +), to reduce the effect that larger and more intensively utilized ponds might have on the study indicators (Table 1). The survey respondents

Table 1 Sample size and distribution by district and religion of respondent

| District | Group | <i>N</i> | Hindu | Muslim |
|-------------------|-----------|----------|-------|--------|
| Site 1 | | | | |
| <i>Khulna</i> | Ecopond | 229 | 59% | 41% |
| <i>Khulna</i> | Control | 208 | 55% | 45% |
| <i>Khulna</i> | Ecopond + | 113 | 63% | 37% |
| <i>Khulna</i> | Control + | 116 | 56% | 44% |
| Site 2 | | | | |
| <i>Barguna</i> | Ecopond | 220 | 4% | 96% |
| <i>Patuakhali</i> | Control | 218 | 7% | 93% |
| <i>Barguna</i> | Ecopond + | 119 | 5% | 95% |
| <i>Patuakhali</i> | Control + | 105 | 4% | 96% |

were the women who received the ecopond training (i.e. ecopond and ecopond + groups) and women from similar control households (i.e. control and control + groups). The questionnaire contained six modules including (a) general household characteristics; (b) fish production; (c) income and expenses; (d) intra-household decision-making; (e) food consumption patterns, and (f) women's empowerment (adapted from the WEAI). More information about the main study variables is included in the next section.

During Phase 3, we conducted focus group discussions (FGDs) to understand the drivers behind food-purchasing priorities. The FGDs were designed following the completion of the analysis of the main survey (Phase 2) and sought to identify why the observed increase of income from ecoponds does not seem to translate into higher dietary diversity as expected (Figure S1, Supplementary Material). The Ladder of Power and Freedom Tool was employed to understand what changes in important life decisions (including food choices) have occurred in households engaged in ecoponds (Petesch and Bullock 2018).

A total of eight FGDs were conducted divided across gender and religion, as these two variables were identified during Phase 1–2 as potential factors influencing food-purchasing decisions (Table S2, Supplementary Material). Each FGD contained 6–7 participants, and when possible both the women who received the ecopond training and their husband were invited to participate (each within their respective FGD group). The participating households were purposely selected based on the survey's results and the key impact pathways identified (Figure S1, Supplementary Material). Specifically FGD participants were randomly selected from the survey participants that exhibited all of the following criteria: (a) had attended ecopond training (i.e. belonged to ecopond or ecopond + groups), (b) exhibited low or borderline dietary diversity in terms of the Food Consumption Score (FCS < 42) (see below), and (c) experienced income generation from the ecoponds.

Data analysis

Main impact variables

Following Figure S1 (Supplementary Material), the main impacts captured in this study include (a) fish production and diversity, (b) household income and expenses, (c) food serving priority, (d) food security, and (e) women's empowerment. Below we outline the main variables and analysis for each of these impact categories.

For fish production and fish species diversity, we estimate total fish production and production per species from all available sources in each household (i.e. ponds, gher, open waters, underutilized ponds/ecoponds). To express different types of productivity, we estimate these variables for the entire household and per unit area.

For income and expenses, we aggregate all major and minor income streams and expenses within the household, captured in Bangladeshi Taka (BDT) and subsequently converted in United States Dollars (USD) (1 USD = 84.5 BDT). Income and expenses are expressed in absolute and Adult Equivalent (AE) values. Since there is no standardized such scale found in Bangladesh official reports, we use the OECD-modified equivalent scale where a value of 1 is assigned to the household head, 0.5 is assigned for each subsequent adult, and 0.3 to each child.

For food serving priority, we requested respondents to use a 5-level Likert scale, to rank the serving, order of all household members, including those that were not present at the moment of the survey (e.g. pregnant women, lactating women). This indicator is used as a proxy for intra-household dynamics.

For food security, we use three different variables that provide complementary views, namely (a) the Food Consumption Score (WFP 2008); (b) fish consumption; (c) diversity of consumed fish. The FCS is a standardized measure of dietary diversity, measuring the consumption of nine standardized food groups over a recall period of seven days (Table S3, Supplementary Material). The overall household fish consumption assesses the availability of fish within the household. The diversity of consumed fish is a proxy for household access to a wider range of micronutrients, due to more diversified fish consumption.

For women's empowerment, we use a modified version of the Women's Empowerment in Agriculture Index (WEAI) (Alkire et al. 2013). We adjusted the WEAI to properly reflect fish production as the main livelihood source and overcome its over-focus on agricultural practices. Nine indicators (out of the original ten) across five dimensions were captured, namely (a) production, (b) resources, (c) income, (d) leadership, and (e) time. One indicator was not captured due to the fact that not all households have access to certain types of productive assets (i.e. farmlands). We calculate the

overall WEAI for each group following the method proposed by Alkire et al. (2013).

We report variable levels for each of the four study groups in each study site. In each site, we compare variable levels only for comparable groups, i.e. “ecoponds vs. control” and “ecoponds + vs. control +”. Treatment outcomes are elicited through (a) the comparison of average variable scores using inferential statistic techniques (i.e. t test for parametric data, Mann–Whitney test for non-parametric data) and (b) Propensity Score Matching (PSM) to reduce possible treatment assignment bias (see next section).

Propensity score matching

The PSM approach has been increasingly used to correct for biases in the adoption of agricultural interventions and to estimate causal treatment effect (Ahmed et al. 2019; Caliendo and Kopeinig, 2005; Dompereh et al. 2020). In this study, we use the PSM to assess how the adoption of the good management practices and training outlined above affect household fish production (in terms of fish species diversity and total fish harvest), income, and food security (captured through the FCS and the diversity of consumed fish species).

For the PSM analysis, we use SPSS version 23 with the PSMatching 3.04 extension. The confounders used in the model include the age of the household member in charge of managing the pond, her total years of schooling, main religion of the household, working status (dummy variable: 0 = engaged in a formal/informal paid job, 1 = otherwise), and number of months within a year the household reported food insecurity as a proxy of unobservable socio-economic variables (Table S4, Supplementary Material).

Multiple matching techniques and setup combination (i.e. use of calipers, discard of units outside the common support group, sub-classification, and match ratio) are employed (Table S5, Supplementary Material). In all analyses, we use the nearest neighbor matching with a combination of calipers at 0.1 and removing units outside the common support group, as it produces the lowest relative multivariate imbalance and thus the best matching (Iacus et al. 2009).

Qualitative analysis of FGDs

The FGDs use a combination of open-ended and Likert scale questions to understand the priority that households ascribe to a diverse diet, the types of expenditures, and intra-household dynamics. The generic Likert scale questions are used to elicit the current food security perceptions within the household and improvement due to the ecopond training and overall intervention. For perceptions of empowerment, we use an adaptation of the ladder of Power and Freedom to elicit each individual’s power and freedom to

make important life decisions (Petesch and Bullock 2018). We calculate the consensus levels for these questions, with a consensus level of “1” representing complete consensus and “0” complete disagreement in the group.

The open-ended questions focus on the diet and expenditure priorities within the participants’ households. Issues that were most discussed by participants are classified as having “high” priority, issues that were somewhat discussed are classified as “medium” priority, and issues that were not mentioned (or were quickly mentioned by one participant) were classified as “low” priority.

Results

Sample characteristics

All groups across both sites share similar general characteristics (Table 2). Household sizes are slightly higher in the study site 2, which is characterized by a Muslim majority. In terms of diet diversity, on average, all groups have an acceptable FCS, with scores higher than the 35 cut-off point. The relevance and importance of ecoponds is evident for all groups, in that they represent the highest or second-highest source of fish for the households.

Fish production and diversity

In both study sites, the households receiving the ecopond training and implementing the recommended production practices produce a higher diversity of fish species compared to their respective control groups, with significant differences in about half of these comparisons (Table 3). In Study Site 1, treatment households without other ponds produce a significantly higher diversity of fish species ($M = 4.65$) compared to their control group ($M = 4.29$) (i.e. ecopond vs. control). Similarly, in Study Site 2, treatment households without other ponds produce a significantly higher diversity of fish species ($M = 4.51$) compared to their control group ($M = 3.83$). Households receiving treatment and have other ponds (ecoponds +) have generally higher fish diversity than their controls (control +), though the differences are not statistically significant. The results are rather similar between the treatment/control sampling method and the PSM method, though in some cases, they have lower significance or are not statistically significant (Table 3).

While for some comparisons control groups produce larger total amounts of fish compared to treatment households (Table S6, Supplementary Material), when adjusted per pond size, households that received ecopond training have consistently a higher productivity per unit area across sites, groups, and statistical tests (Table 4). For example, in Study Site 1, control groups had a higher total fish

Table 2 Household characteristics by study site and group

| Indicator | Study site 1 | | | | Study site 2 | | | |
|--|--------------|---------|----------|----------|--------------|---------|----------|----------|
| | Ecopond | Control | Ecopond+ | Control+ | Ecopond | Control | Ecopond+ | Control+ |
| <i>General characteristics</i> | | | | | | | | |
| Sample size (number) | 229 | 208 | 113 | 116 | 220 | 218 | 119 | 105 |
| Age of respondent (years) | 40 | 39 | 39 | 40 | 41 | 40 | 42 | 39 |
| Education of respondent (years) | 5.3 | 5.3 | 6.3 | 5.9 | 4.7 | 4.8 | 4.5 | 5.7 |
| Household Size (persons) | 4.3 | 4.2 | 4.5 | 4.4 | 4.8 | 4.6 | 4.8 | 4.8 |
| Food consumption score (units) | 65.8 | 63.6 | 65.9 | 69.8 | 63.6 | 61.6 | 64.9 | 67.7 |
| <i>Fish production by source (kg/year)</i> | | | | | | | | |
| Pond | 0.0 | 0.0 | 35.9 | 67.9 | 0.0 | 0.0 | 113.0 | 99.6 |
| Gher | 0.0 | 0.0 | 124.1 | 188.4 | 0.0 | 0.0 | 17.1 | 25.1 |
| Open water | 32.8 | 69.4 | 19.8 | 20.4 | 21.9 | 57.9 | 20.9 | 27.4 |
| Buy fish | 44.2 | 28.8 | 48.3 | 23.9 | 50.2 | 60.9 | 44.9 | 44.5 |
| Received as gift | 5.6 | 1.6 | 2.3 | 1.6 | 0.6 | 0.3 | 0.5 | 0.4 |
| Ecopond//underutilized pond | 88.9 | 74.6 | 79.4 | 62.1 | 135.1 | 68.1 | 97.0 | 61.6 |

Table 3 Diversity of produced fish species across sampling groups, study sites and statistical tests

| | Sampling groups | | | Propensity score matching | | |
|---------------------------------------|-----------------|---------|----------|---------------------------|------------------|----------|
| | Treated | Control | Sig | After treatment | Before treatment | Sig |
| <i>Fish species diversity (Count)</i> | | | | | | |
| <i>Study site 1</i> | | | | | | |
| Ecopond vs control | 4.65 | 4.29 | 0.010** | 4.62 | 4.33 | 0.076 |
| Ecopond + vs control + | 5.50 | 5.22 | 0.311 | 5.52 | 5.26 | 0.165 |
| Study site 2 | | | | | | |
| Ecopond vs control | 4.51 | 3.83 | 0.000*** | 4.43 | 3.84 | 0.001*** |
| Ecopond + vs control + | 5.29 | 4.88 | 0.033* | 5.45 | 4.82 | 0.010** |

Note: *** $p < 0.001$; ** $p < 0.01$, * $p < 0.05$

production (control $M = 144.0$; control + $M = 338.8$, respectively) compared to the Ecopond treatment groups (ecoponds $M = 121.6$; ecoponds + $M = 259.3$, respectively) (Table S6, Supplementary Material). However, when compared in terms of fish production per unit area, ecopond treatment groups have a higher fish production (without considering fish harvested from open waters) compared to their respective control groups (Table 4). In Study Site 2, Ecopond treatment groups have a higher total fish production (ecopond $M = 157.1$, ecopond + $M = 247.9$, respectively) compared to their control groups (control $M = 125.9$, control + $M = 213.7$) (Table S6, Supplementary Material). However, when comparing their production per unit area, we find a statistically significant difference between total fish production per unit area in Ecopond treatments (ecopond $M = 16.89$, ecopond + $M = 27.89$) compared to their respective control groups (control $M = 11.86$, control + $M = 20.19$, respectively) (Table 4).

It is worth noting that despite variations in total fish production across the different types of ponds/areas used for fish

production between groups (Table S6, Supplementary Material), ecoponds exhibit the highest fish productivity per unit area compared to gher or any other type of ponds (Table S7, S8, Supplementary Material). All the patterns outlined above have rather similar means between groups measured through t test inferential statistics and the PSM analysis (Table 4 and Table S6, S7, S8 Supplementary Material).

Income and expenditure

Across all study sites, ecoponds play a major role for income generation, accounting for up to 70% of the total income from fish sales for households not having other ponds (Table 5). In Study Site 1, while ecopond groups produce significantly more fish from ecoponds ($M = 89$ kg compared to their control group from similar underutilized ponds ($M = 75$ kg) (Table S7, Supplementary Material), they have a lower income from fish sales from ecoponds/underutilized ponds per adult equivalent ($M = 51$ USD/AE/year) compared to their control group ($M = 60$ USD/AE/

Table 4 Fish productivity across sampling groups, study sites and statistical tests (in kg/decimal/year)

| Sampling Group | Sampling groups | | | Propensity score matching | | |
|-----------------------------|-----------------|---------|----------|---------------------------|------------------|----------|
| | Treated | Control | Sig. | After treatment | Before treatment | Sig. |
| <i>Study site 1</i> | | | | | | |
| <i>Ecopond vs control</i> | | | | | | |
| Anabas/Perch | 0.60 | 0.31 | 0.022* | 0.63 | 0.27 | 0.015* |
| Catfish | 1.54 | 0.96 | 0.104 | 1.48 | 0.97 | 0.170 |
| Carp | 6.82 | 6.39 | 0.561 | 6.53 | 6.43 | 0.900 |
| Small indigenous fish | 1.19 | 0.71 | 0.000*** | 1.26 | 0.72 | 0.000*** |
| Snakehead | 1.02 | 0.71 | 0.021* | 1.04 | 0.70 | 0.028* |
| Tilapia | 4.35 | 3.24 | 0.025* | 4.44 | 3.19 | 0.029* |
| Other | 0.66 | 0.53 | 0.539 | 0.68 | 0.57 | 0.638 |
| Total | 16.18 | 12.84 | 0.005** | 16.06 | 12.85 | 0.000*** |
| <i>Ecopond+ vs Control+</i> | | | | | | |
| Anabas/Perch | 0.88 | 0.41 | 0.000*** | 0.89 | 0.41 | 0.001** |
| Catfish | 2.04 | 0.84 | 0.016* | 2.21 | 0.85 | 0.020* |
| Carp | 10.33 | 11.23 | 0.580 | 10.45 | 11.73 | 0.458 |
| Small indigenous fish | 2.44 | 1.06 | 0.001** | 1.96 | 1.12 | 0.015* |
| Snakehead | 2.00 | 1.16 | 0.007** | 1.80 | 1.18 | 0.031* |
| Tilapia | 6.01 | 4.41 | 0.127 | 6.11 | 4.39 | 0.143 |
| Other | 1.31 | 1.63 | 0.421 | 1.40 | 1.72 | 0.497 |
| Total | 25.01 | 20.74 | 0.116 | 24.82 | 21.42 | 0.000*** |
| <i>Study site 2</i> | | | | | | |
| <i>Ecopond vs control</i> | | | | | | |
| Anabas/Perch | 0.37 | 0.12 | 0.000*** | 0.37 | 0.12 | 0.001*** |
| Catfish | 2.38 | 2.28 | 0.806 | 2.37 | 2.37 | 0.999 |
| Carp | 5.93 | 4.50 | 0.005** | 5.88 | 4.74 | 0.043* |
| Small indigenous fish | 0.91 | 0.59 | 0.010* | 0.93 | 0.54 | 0.004** |
| Snakehead | 0.74 | 0.35 | 0.000*** | 0.72 | 0.36 | 0.002** |
| Tilapia | 4.27 | 2.78 | 0.015* | 4.46 | 2.99 | 0.028* |
| Other | 2.29 | 1.23 | 0.436 | 2.52 | 0.95 | 0.307 |
| Total | 16.89 | 11.86 | 0.022* | 17.24 | 12.05 | 0.000*** |
| <i>Ecopond+ vs control+</i> | | | | | | |
| Anabas/Perch | 0.67 | 0.54 | 0.358 | 0.77 | 0.49 | 0.099 |
| Catfish | 4.87 | 3.79 | 0.391 | 5.12 | 3.72 | 0.397 |
| Carp | 9.47 | 8.24 | 0.414 | 9.55 | 7.46 | 0.203 |
| Small indigenous fish | 2.13 | 1.03 | 0.000*** | 1.89 | 0.97 | 0.000*** |
| Snakehead | 1.14 | 0.91 | 0.271 | 1.21 | 0.90 | 0.175 |
| Tilapia | 6.62 | 4.38 | 0.002** | 6.68 | 4.19 | 0.01** |
| Other | 2.99 | 1.30 | 0.015* | 3.17 | 1.52 | 0.050* |
| Total | 27.89 | 20.19 | 0.002** | 28.39 | 19.25 | |

Note: Small indigenous fish include mola, darkina, small chingri, punti, and other species rich in micronutrients. The decimal is a local unit of area equivalent 1 dec=0.004 ha; Fish harvest per unit area does not include fish species harvested from open waters; *** $p < 0.001$; ** $p < 0.01$, * $p < 0.05$

year) (Table 5). In Study Site 2, we found that in all cases, ecopond treatment groups have a higher income per adult equivalent from fish sales from ecoponds (ecoponds: $M = 86$ and ecoponds + : $M = 69$ USD/AE/year, respectively) compared to the sales of their control groups from underutilized ponds (control: $M = 50$ and control + : $M = 52$ USD/AE/year, respectively).

In terms of household expenditures, across all comparisons in both study sites, the households that received the treatment spend less money for purchasing fish compared to their respective control groups (Table S9, Supplementary Material), but the differences are mostly not statistically significant. Although across all groups, the highest household expenditure is for purchasing food items other than fish, the

Table 5 Household income across sampling groups, study sites and statistical tests (in USD/AE/year)

| | Sampling groups | | | Propensity score matching | | |
|--|-----------------|---------|---------|---------------------------|------------------|---------|
| | Treated | Control | Sig | After treatment | Before treatment | Sig |
| <i>Study site 1</i> | | | | | | |
| <i>Ecopond vs control</i> | | | | | | |
| Agriculture | 221 | 161 | 0.057 | 194 | 170 | 0.235 |
| Ecopond/underutilized pond fish sales | 51 | 60 | 0.170 | 49 | 62 | 0.084 |
| Other fish sales | 29 | 35 | 0.405 | 26 | 37 | 0.160 |
| Part/Full time employment | 374 | 416 | 0.477 | 372 | 412 | 0.551 |
| Livestock sales | 68 | 83 | 0.151 | 71 | 88 | 0.131 |
| Other income activity | 76 | 35 | 0.078 | 82 | 33 | 0.072 |
| Total Income | 818 | 789 | 0.683 | 794 | 801 | 0.926 |
| <i>Ecopond + vs control +</i> | | | | | | |
| Agriculture | 200 | 388 | 0.001** | 206 | 421 | 0.002** |
| Ecopond//underutilized pond fish sales | 41 | 37 | 0.559 | 42 | 37 | 0.535 |
| Other fish sales | 145 | 240 | 0.004** | 139 | 265 | 0.001** |
| Part/Full time employment | 392 | 392 | 0.996 | 411 | 330 | 0.424 |
| Livestock sales | 72 | 86 | 0.336 | 72 | 86 | 0.410 |
| Other income activity | 56 | 56 | 0.998 | 62 | 47 | 0.597 |
| Total income | 907 | 1,200 | 0.025* | 932 | 1,185 | 0.061 |
| <i>Study site 2</i> | | | | | | |
| Ecopond vs control | | | | | | |
| Agriculture | 191 | 171 | 0.486 | 200 | 178 | 0.485 |
| Ecopond//underutilized pond fish sales | 86 | 50 | 0.101 | 87 | 51 | 0.148 |
| Other fish sales | 37 | 25 | 0.463 | 39 | 24 | 0.397 |
| Part/Full time employment | 508 | 597 | 0.082 | 527 | 600 | 0.172 |
| Livestock sales | 102 | 97 | 0.750 | 110 | 104 | 0.738 |
| Other income activity | 96 | 180 | 0.011* | 85 | 175 | 0.013* |
| Total Income | 1,020 | 1,120 | 0.143 | 1,048 | 1,132 | 0.273 |
| <i>Ecopond + vs control +</i> | | | | | | |
| Agriculture | 218 | 226 | 0.818 | 225 | 214 | 0.762 |
| Ecopond//underutilized pond fish sales | 69 | 52 | 0.027* | 68 | 50 | 0.040* |
| Other fish sales | 108 | 113 | 0.792 | 113 | 102 | 0.650 |
| Part/Full time employment | 618 | 458 | 0.072 | 644 | 475 | 0.165 |
| Livestock sales | 117 | 129 | 0.577 | 117 | 120 | 0.922 |
| Other income activity | 61 | 141 | 0.063 | 61 | 163 | 0.055 |
| Total income | 1,191 | 1,119 | 0.494 | 1,229 | 1,124 | 0.339 |

Note: *** $p < 0.001$; ** $p < 0.01$, * $p < 0.05$

groups with ecopond treatment tend to spend comparatively less money to purchase other types of food (Table S9, Supplementary Material).

Dietary diversity and eating order

There is no significant difference in terms of dietary diversity (i.e. FCS) between treatment and control groups in any of the study sites (Table 6). For all study groups, the obtained FCS scores are above the threshold of 39 points, indicating a rather acceptable food security in terms of dietary diversity. Overall, most treatment groups have a

slightly higher FCS compared to their control groups, while the Ecopond + groups have a slightly lower FCS compared to their control groups. However, in all cases, treatment groups consume a higher diversity of fish species compared to their respective control groups, with the differences having no or low statistical significance (Table 6).

However, all Ecopond treatment groups consume higher quantities of fish per adult equivalent compared to their respective control groups, but with not all differences being statistically significant (Table S10, Supplementary Material). In Study Site 1, Ecopond group consumes significantly more fish per adult equivalent ($M = 55.26$ kg/AE/year)

Table 6 Dietary diversity and diversity of consumed fish species across sampling groups, study sites and statistical tests

| | Sampling groups | | | Propensity score matching | | |
|---------------------------------------|-----------------|---------|---------|---------------------------|------------------|---------|
| | Treated | Control | Sig | After treatment | Before treatment | Sig |
| <i>Dietary diversity (FCS)</i> | | | | | | |
| <i>Study Site 1</i> | | | | | | |
| Ecopond vs Control | 65.8 | 63.6 | 0.227 | 65.8 | 64.8 | 0.616 |
| Ecopond + vs Control + | 65.9 | 69.8 | 0.103 | 64.7 | 70.4 | 0.023* |
| <i>Study Site 2</i> | | | | | | |
| Ecopond vs Control | 63.6 | 61.6 | 0.271 | 64.1 | 62.3 | 0.346 |
| Ecopond + vs Control + | 64.9 | 67.7 | 0.218 | 65.3 | 66.8 | 0.564 |
| Fish Species Diversity (Count) | | | | | | |
| <i>Study Site 1</i> | | | | | | |
| Ecopond vs Control | 5.46 | 5.13 | 0.017* | 5.46 | 5.14 | 0.012* |
| Ecopond + vs Control + | 5.81 | 5.27 | 0.006** | 5.80 | 5.26 | 0.004** |
| <i>Study site 2</i> | | | | | | |
| Ecopond vs control | 5.41 | 5.14 | 0.036* | 5.34 | 5.17 | 0.189 |
| Ecopond + vs control + | 5.74 | 5.71 | 0.722 | 5.85 | 5.73 | 0.497 |

Note: *** $p < 0.001$; ** $p < 0.01$, * $p < 0.05$

Table 7 Modified WEAI and household fraction with women's empowerment adequacy across groups and study sites

| Sampling group | WEAI | | Empowerment adequacy | | |
|------------------------|-------------------|------------------------|----------------------|-------------------|--------|
| | Treatment (score) | Control groups (score) | Treatment (% of HH) | Control (% of HH) | Sig |
| <i>Study site 1</i> | | | | | |
| Ecopond vs control | 85% | 80% | 77% | 67% | 0.020* |
| Ecopond + vs control + | 83% | 84% | 74% | 75% | 0.908 |
| <i>Study site 2</i> | | | | | |
| Ecopond vs control | 84% | 81% | 69% | 62% | 0.115 |
| Ecopond + vs control + | 86% | 81% | 74% | 59% | 0.018* |

Note: *** $p < 0.001$; ** $p < 0.01$, * $p < 0.05$

compared to their control group ($M = 43.94$ kg/AE/year). Moreover, across all comparisons in both study sites, the consumed quantity of fish by species is often higher among Ecopond treatment groups, compared to their respective control groups.

There is no significant difference in the periods of self-reported food insecurity between study groups in any of the study sites (Table S11 Supplementary Material). While the proportion of household reporting monthly food insecurity peaks at 7% and 5%, respectively, the actual period when this occurs differs between sites (Figure S5, S6, Supplementary Material). In Study Site 1, the self-reported period of food insecurity starts in the second quarter of the year (May–Aug) and peaks during the last quarter of the year (Sep–Oct) (Figure S5, Supplementary Material). However, food insecurity peaks during the second quarter of the year (May–Aug) in Study Site 2 (Figure S6, Supplementary Material).

Regarding intra-household dynamics, there is no evidence of significant change between groups in terms of eating order including vulnerable groups, such as pregnant and lactating

women, in any of the study sites (Table S12, Supplementary Material). However, it is noteworthy to mention that results show men often have a higher serving priority compared to women for a given group.

Women's empowerment

As mentioned in the Methodology, we calculate the overall empowerment score for each group along the five dimensions of (a) production (input to and autonomy in production), (b) resources (access to and decisions on credit as well as ownership of resources), (c) income (control over use), (d) leadership (group membership and speaking in public), and (e) time (leisure and workload).

The results indicate the slightly higher overall women's empowerment among Ecopond treatment groups in terms of the absolute modified WEAI, compared to their control counterparts, for 3 out of the 4 group comparisons for both tests (Table 7). However, in most cases, the difference is not statistically significant between group comparisons

Table 8 Focus group discussion outcomes for the Likert scale questions

| | Consumption of sufficient and preferred food | | Freedom to make major household decisions | | Improvement of decision-making power following ecopond training | |
|------------------------|--|-----------|---|-----------|---|-----------|
| | Level ¹ | Consensus | Level ² | Consensus | Level ³ | Consensus |
| FGD 1 (Women, Barguna) | 7.7 | 0.89 | 3.2 | 0.66 | 3.7 | 0.86 |
| FGD 2 (Women, Barguna) | 7.6 | 0.71 | 2.7 | 0.56 | 3.1 | 0.76 |
| FGD 3 (Women, Khulna) | 7.4 | 0.86 | 4.0 | 0.48 | 3.9 | 0.93 |
| FGD 4 (Women, Khulna) | 6.4 | 0.76 | 3.6 | 0.67 | 3.9 | 0.76 |
| FGD 5 (Men, Barguna) | 5.5 | 0.70 | 3.5 | 0.81 | 2.2 | 0.82 |
| FGD 6 (Men, Barguna) | 8.3 | 0.90 | 3.6 | 0.74 | 3.4 | 0.85 |
| FGD 7 (Men, Khulna) | 6.7 | 0.81 | 3.7 | 0.75 | 3.9 | 0.85 |
| FGD 8 (Men, Khulna) | 6.0 | 0.90 | 5.0 | 1.00 | 4.0 | 0.82 |

Note: ¹Scale from 1 (not at all) to 10 (very much); ²Scale from 1=Almost no power or freedom to make decisions, 2=Only a small amount of power & freedom, 3=Power & freedom to make some major life decisions, 4=Power & freedom to make many major life decisions, 5=Power & freedom to make most or all major life decisions; ³Scale from 1=No improvement, 2=Improved to have small power on major life decisions, 3=Improved to have some power on major life decisions, 4=Improved to have major power on major life decisions, 5=Improved to have most power on major life decisions

(Table 7). It is interesting to point that there are no clear differences between scores for similar groups from Study Site 1 that contains an equal mix of Hindu and Muslim households, and Study Site 2 that contains predominantly Muslim households (Table 1).

When looking at the individual dimensions of women's empowerment, one of the most interesting findings is that the majority of women engaged in small-scale aquaculture in underutilized ponds controls the relevant income (see indicator I1, Table S13, Supplementary Material). Ecoponds households have a generally higher empowerment adequacy in this dimension, but the difference is not statistically significant in any of the comparisons with control households. However, when it comes to asset ownership (indicator R1), ecoponds households have significantly higher empowerment adequacy than control households in most comparisons.

Consistently the lowest empowerment adequacy is for the "access to and decisions over credit" (see indicator R3, Table S13, Supplementary Material). Again even though ecoponds households have higher empowerment adequacy for this dimension, the differences are not statistically significant with control groups. Finally, it is worth noting that empowerment adequacy for workload indicator is higher (but not significantly) for two of the comparisons with control groups, and the same for the other two (see indicator T1, Table S13, Supplementary Material).

Focus group discussion analysis

As outlined above, the FGDs consisted of purposefully selected households that had reported income gains from

engagement in ecopond activities but had low or borderline dietary diversity in terms of the FCS. Through this extra layer of analysis, we sought to understand whether income from ecopond activities is invested to buy other food items, and if not, why.

First, the women FGD participants attested that they have the freedom to make some major life decisions, including allocation of household expenses for consumption decisions, and that participation in the ecopond intervention has improved to some extent this ability, with some high degree of consensus (Table 8). This suggests that in theory those women could invest their ecopond income to buy food to increase dietary diversity within the household.

However, even though there is an overall understanding of the value of a preferred and nutritious diet and its prioritization over absolute quantity, it seems that other priorities within the household take precedence (Fig. 1). In particular, participants across all FGDs articulated a lower priority towards spending any extra income for diet diversification. Instead, education and increased productivity are viewed as the main priorities (Fig. 1), or as one participant mentioned "spending the extra income on increasing productivity will give me more profit. Then I can use the profit for family welfare" (Participant 1, FGD3).

Follow-up questions regarding challenges to diversify household diet did not reveal major barriers regarding decisions over food expenditures. For example, one of the participants suggested that: "if there is any need for my family, I tell my husband and he never refuses me [...], the money earn by selling these [fish] remains in my hand" (Participant 2, FGD 2).

Fig. 1 Focus group discussion outcomes for the open-ended questions

| | FGD1 | FGD2 | FGD3 | FGD4 | FGD5 | FGD6 | FGD7 | FGD8 |
|-------------------------------|------|------|------|------|------|------|------|------|
| Diet priorities | | | | | | | | |
| Food quantity | ■ | ■ | ▲ | ■ | ■ | ▲ | ▼ | ▼ |
| Eat preferred food | ▲ | ▲ | ▲ | ▼ | ▲ | ▲ | ■ | ▲ |
| Nutrition | ▲ | ■ | ▼ | ▲ | ▲ | ▼ | ▲ | ▲ |
| Expenditure priorities | | | | | | | | |
| Children education | ▲ | ■ | ▲ | ▲ | ▲ | ■ | ▲ | ▲ |
| Increase productivity | ▲ | ▲ | ▼ | ▲ | ▲ | ▲ | ▲ | ▲ |
| Healthcare and welfare | ▲ | ■ | ■ | ■ | ▼ | ■ | ■ | ■ |
| Food diversity | ▼ | ▼ | ■ | ■ | ▼ | ▼ | ▼ | ▼ |

▲ = High priority
 ■ = Medium priority
 ▼ = Low priority

Fig. 2 Schematic representation of impact pathways and observed trends

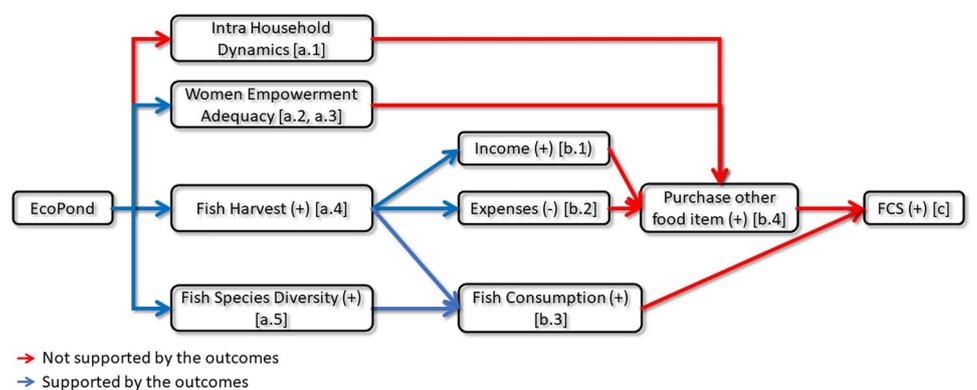


Fig. 3 Summary of sustainability impacts by study site and group comparison

| EcoPond Treatment | Study Site 1 | | | | Study Site 2 | | | | Total | |
|--|----------------|---------------|----------------|---------------|----------------|---------------|----------------|---------------|------------|----------|
| | EcoPond Result | EcoPond+ Sig. | Higher (%) | Sig. (%) |
| [a.1] Intra-household dynamics | ↓ | - | ↓ | - | ↓ | - | ↓ | - | ○ | - |
| [a.2] WEAI | ↑ | - | ↓ | - | ↑ | - | ↑ | - | ○ | - |
| [a.3] HH with women empowerment adequacy | ↑ | ✓ | ↓ | ✗ | ↑ | ✗ | ↑ | ✓ | ● | ● |
| [a.4] Increase EcoPond harvest (per decimal) | ↑ | ✓ | ↑ | ✓ | ↑ | ✓ | ↑ | ✓ | ● | ● |
| [a.5] Increase in fish varieties | ↑ | ✓ | ↑ | ✓ | ↑ | ✓ | ↑ | ✓ | ● | ● |
| [b.1] Higher income from ecoPonds (per AE) | ↓ | ✗ | ↑ | ✗ | ↑ | ✓ | ↑ | ✓ | ● | ● |
| [b.2] Decrease expenditure on fish (per AE) | ↑ | ✗ | ↑ | ✗ | ↑ | ✓ | ↑ | ✓ | ● | ● |
| [b.3] Higher fish consumption (per AE) | ↑ | ✓ | ↑ | ✗ | ↑ | ✗ | ↑ | ✗ | ● | ● |
| [b.4] Purchase other food items (per AE) | ↓ | ✓ | ↓ | ✓ | ↓ | ✗ | ↓ | ✗ | ○ | ○ |
| [c] Higher Food Consumption Score | ↑ | ✗ | ↓ | ✗ | ↑ | ✗ | ↓ | ✗ | ○ | ○ |

↑ = Outcome higher than its respective control group
 ↓ = Outcome lower than its respective control group
 ✓ = Outcome significantly higher/lower than its respective control group
 ✗ = Outcome not significantly higher/lower than its respective control group

○ = 0% (0 cases)
 ◐ = 25% (1 cases)
 ◑ = 50% (2 cases)
 ◒ = 75% (3 cases)
 ● = 100% (4 cases)

Impact pathways outcomes

Figures 2, 3 summarize the main findings of this study across the studied sustainability impacts. Overall, the results suggest that the intensification of small-scale aquaculture systems through ecosystem approaches for habitat provision can offer positive yet inconsistent benefits. In

summary, the main impacts of the EcoPonds intervention can be summarized as:

- significant productivity and livelihood gains;
- moderate women’s empowerment gains;
- inconsistent food security outcomes.

These findings point to the real potential of ecosystem-based approaches to small-scale aquaculture. However, as outlined in the Discussion, in order to achieve these sustainability benefits, it is necessary to understand some of the underlying mechanisms, as well as tackle constraints, especially those related to education, and broader cultural and socioeconomic factors.

Discussion

Significant productivity and livelihood gains

Notably, ecoponds have higher fish diversity, fish productivity per unit area, and income generation potential compared to similar underutilized ponds (Tables 3, 4). This is evident in most group comparisons and is in most cases statistically significant (Fig. 3). Furthermore, per unit area, ecoponds are more productive than other types of ponds or ghers in the study areas, while ecopond fish productivities are higher in households that do not have other ponds (Table S8, Supplementary Material). This shows that indeed ecoponds can offer substantial productivity and livelihood benefits, suggesting their large potential for rural development in Bangladesh, and possibly other developing contexts. However, it is not clear from our results why these higher productivity manifest. For example, it might be that households that have other larger ponds do not invest significant input to household ecoponds (Chowdhury 2009), that the women involved in ecopond activities are willing to invest more time and care on managing the ecopond habitats, or that they harvest fish more regularly due to the limited other fish supply alternatives. Such mechanisms need to be understood better to further ascertain the potential for upscaling such aquaculture practices in Bangladesh and other similar developing contexts.

Moderate women's empowerment gains

A very crucial element of the study is that the ecoponds were actively managed by women, many of whom were not previously involved directly in fish production in their own ponds. As mentioned in the Introduction, women are mostly engaged in aquaculture in post-harvest activities, such as marketing and processing, but their role is often under-recognized or 'hidden' in value chain analyses (Eltholth et al. 2015; Shirajee et al. 2010; Kruijssen et al. 2018; Choo and Williams 2014; Gopal et al. 2014). In this study, there are some signs that engagement in ecoponds training and production is associated with higher women's empowerment, which is relatively uncommon considering this "hidden" role of women in Bangladesh aquaculture (Ahmed et al. 2012)

(see also Introduction). In particular, there are relatively higher absolute WEAI scores for some treatment groups, but these improvements are not statistically significant (Table 7, Table S13, Supplementary Material; Fig. 3). However, ecopond households have higher empowerment adequacy for individual indicators, such as control of income and productive assets, with the latter being statistically significant for most comparisons (Table S13, Supplementary Material). Furthermore, some of the women FGD participants also indicate that the participation in ecopond training improved their ability/capacity to make major household decisions, but admittedly due to the confining participant selection criteria this might not be generalizable for the entire sample (Table 8).

Collectively, the above suggest that ecoponds indeed contribute to some aspects of women's empowerment by increasing their power over these underutilized ponds to improve productivity (via capacity-building) and the power to act on the training knowledge, as indeed evidenced in other small-scale aquaculture and fisheries contexts (Manungwa et al. 2019; Park 2017; Frangoudes et al. 2019). However, it did not address power within or power with, such as the gender power relations that inhibit women's empowerment at multiple scales, thus leaving structural inequalities at large. The above suggest ecoponds have some women's empowerment potential but achieving women's empowerment in rural Bangladesh is a multifaceted process and/or that the ecoponds intervention only covers some of the important components of women's empowerment (i.e. control over ecoponds and ecopond income). This does not necessarily translate to control over other important life choices that Naila Kabeer's definition points towards, as again pointed in multiple other studies in small-scale aquaculture and fisheries contexts (Kruijssen et al. 2018; Cole et al. 2020).

In any case, even these moderate women's empowerment outcomes can be source of optimism, considering the general lack of women access and control over productive resources in rural contexts of Bangladesh (Ahmed et al. 2012; Aregu et al. 2018; Choudhury et al. 2017; Farnworth et al. 2016; Halim and Ahmed 2006; Shelly and D'Costa 2001). To further improve these aspects, Gender Transformative Approaches (GTA) can be built into the extension model to address the underlying social barriers women face, possibly sparking critical discussions on intra-household dynamics and gender norms (Choudhury and Castellanos 2020; Kantor et al. 2015; Cole et al. 2020). While "gender accommodative" approaches acknowledge these barriers but propose to "work around them", GTAs seek to reduce them by creating awareness about the gender roles and norms that lead to them (Cole et al. 2020). Essentially, projects using GTAs design-specific strategies and actions to contribute to behavioral changes in both men and women (Hillenbrand

et al. 2014). In the context of our case study, a GTA could be one that helps translate to important elements of women's empowerment beyond aquaculture such as improve access to credit, which is by far the dimension of empowerment with consistently the lowest empowerment adequacy among all groups (Table S13, Supplementary Material). Furthermore, other GTAs could help address gender power relations that form structural barriers to women's empowerment across multiple scales (Wong et al. 2019; Kantor et al. 2015; Aregu et al. 2019).

Inconsistent food security outcomes

Interestingly, despite the gains in productivity, income, and empowerment described above, ecoponds have a relatively inconsistent impact on food security. On the one hand, it is evident across most comparisons that ecoponds/ecoponds + households consume more and more diverse fish, with the differences being statistically significant for many comparisons (Table 6; Fig. 3). Even though, carp and tilapia output and consumption are the highest in absolute terms among the different aquaculture species, there are also significant differences in the production and consumption of small indigenous fish among some groups (Table S6 and S10, Supplementary Material). These species are rich in micronutrients (e.g. vitamin A, iron, zinc, calcium) and have thus been identified as a possible option for reducing malnutrition among poor households and vulnerable groups (e.g. pregnant women, small children, lactating mothers) (Karim et al. 2017; Bogard et al. 2015), suggesting possible nutritional benefits for ecopond groups.⁴

However, the overall impacts of ecoponds on diet diversity (Table 6) or intra-household eating dynamics (Table S12, Supplementary Material) are not conclusive. As outlined during the FGDs, this lack of strong impact on dietary diversity might be likely due to the low prioritization of diversified diets compared to other household expenditures rather than women's control of income sources (see "FGD analysis" and Table S13, Supplementary Material). Previous studies have found that health and dietary concerns in rural areas characterized by low access to resource do not necessarily translate into more diversified dietary choices regardless of the food cost, partly due to misconceptions about the importance of certain food groups (Farris et al. 2020) and prioritization of income expenditure on other competing household needs, such as healthcare and education (Hendriks and Lyne 2003). Such mechanisms need to

be understood better to understand better the food security potential of ecoponds in Bangladesh, and possibly improve the training necessary training packages.

Implications and recommendations

The results of this study clearly show that the intensification of small-scale aquaculture systems through ecosystem approaches has multiple sustainability benefits. In this sense, such interventions can help achieve localized progress across multiple Sustainable Development Goals (SDGs), such as SDG1 (No Poverty), SDG2 (Zero Hunger), SDG5 (Gender Equality) and SDG14 (Life Below Water), among others.

However, our results also show that the impacts do not manifest always manifest equally across all sustainability dimensions, often due to underlying constraints, such as lack of education or prevailing cultural and socioeconomic conditions. This strongly implies that to achieve the full potential of aquaculture (and more broadly development) interventions, the design and dissemination of new innovations must not only account for the expected sustainability outcomes (e.g. improved food security, poverty alleviation, gender empowerment), but also for the capacities and cultural and socioeconomic barriers that the target groups must overcome.

Towards that end, conducting ex-ante evaluations (e.g. defining locally appropriate theories of change, identifying impact mechanisms) and understanding the cultural and socioeconomic context of the intervention area (e.g. underlying gender norms, household investment priorities) can help design interventions with high impact that reach those who need it the most.

Furthermore, complementing the dissemination of aquaculture innovations with GTAs can possibly contribute to positive and long-lasting sustainability outcomes. Drawing from the lessons learnt from this study, some relevant activities might include:

- involve and empower all relevant local actors (e.g. men, women, community leaders) across multiple entry points (e.g. household level, community level, local formal and informal institutions);
- engage such actors in self-reflection exercises that best accommodate the intervention context (e.g. workshops, role play, drama plays, games), where cultural and socioeconomic barriers and restrictive gender norms can be identified, and their possible effect for the expected outcomes become clear;
- persuade each actor to takes responsibility of their role in challenging these cultural and socio-economic norms and overcome the barriers that could constrain the sustainability outcomes of the intervention.

⁴ It is worth mentioning that the production of such a diverse set of species can help maintain aquatic biodiversity in Bangladesh (ICSF, 2010), especially considering the widespread degradation of aquatic habitats and the overexploitation of fish stocks from rivers, canals, and other wetlands in the country.

Conclusion

This study suggests that the intensification of small-scale aquaculture systems through ecosystem approaches that provide habitat to fish in underutilized ponds can have multiple positive sustainability impacts. In particular, these ecoponds are associated with higher fish productivity, fish species diversity, and income generation potential. Furthermore, the active involvement of women in their development and operation can have some women's empowerment benefits in terms of control of income and productive assets, which are very important in the socio-cultural context of rural Bangladesh. Indeed engagement with ecoponds seems to generate greater confidence among women to take more initiative in fish aquaculture, rather than their usual role in downstream fish processing activities. In this case, women's access and active participation in homestead aquaculture increased their basic understanding on fish production technologies, and ability to utilize them effectively. However, despite its positive effect on some aspects of women's empowerment, the intervention did not affect wider gender inequality aspects and gender roles. Furthermore, the food security outcomes are rather inconclusive, possibly due to the lower prioritization of diversified diets in the context of household expenditures.

The above suggest that the intensification of small-scale aquaculture systems through ecosystem approaches can help achieve localized progress across multiple SDGs. However, there is a need to strengthen certain impact pathways to further improve food security and women's empowerment. While some can become parts of the intervention package (e.g. education about diversified diets and nutrition) others might reflect broader cultural and socio-economic constraints that could be beyond the domain of a single intervention. The comparative effects of such mechanisms need to be understood better and to the extent approached through targeted GTAs to further ascertain the potential for upscaling such ecosystem approaches to small-scale aquaculture in Bangladesh and other similar developing contexts.

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Declarations

Conflict of interest The ecopond project intervention (Ecopond I and II) evaluated in this study was designed and implemented by WorldFish Bangladesh in collaboration with partners. Some of the co-authors in this study are affiliated with WorldFish.

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