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Tilapia aquaculture systems in Egypt: Characteristics, sustainability outcomes and entry points for sustainable aquatic food systems

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ABSTRACT

The future demand for fish and other aquatic foods requires the sustainable intensification of related production systems. However, policy and investment decisions for the sustainable intensification of aquaculture systems are usually hindered by the lack of benchmarking data about their actual sustainability performance, often resulting in poorly developed and implemented interventions that ignore potential sustainability trade-offs. This is a reality in many of the leading aquaculture producers in the developing world like Egypt. In this study we analyzed farm-level data from 402 aquaculture producers in the Kafr El Sheikh governorate in Egypt, to characterize and benchmark the performance of tilapia production systems against key sustainability outcomes. For the analysis we used a combination of statistical tools such as ordinary least square regressions, simultaneous quantile regressions and propensity score matching. We focussed on how the production characteristics and practices of different tilapia production systems intersect with economic, food security, and environmental outcomes that cover multiple dimensions of sustainability. We found that differences in these production characteristics and practices were significantly associated with the sustainability performance of tilapia production systems. In particular, our results show that yields in monocultural systems (10,460.5 ton/ha) were significantly higher than in polyculture systems (8404.7 ton/ha). Furthermore, despite the generally positive economic, food security, and environmental outcomes of several of the studied systems, some trade-offs emerge both between and within these sustainability dimensions.

1. Introduction

Meeting the food demand and nutritional needs of the growing global population, while staying within planetary boundaries, is one of the greatest sustainability challenges facing humanity today. Food systems are at the center of this challenge, not the least because their rapid transformations over the past three decades have had major ramifications for sustainability (HLPE., 2020; United Nations Environment Programme (UNEP), 2016). Recent literature on food systems suggests that transitioning to sustainable food systems should entail, among others, the promotion and adoption of socio-technical innovations and approaches that are able to deliver multiple benefits across equally multiple socio-economic and environmental dimensions (Klerkx and Begemann, 2020).

This is particularly pertinent for aquatic food systems, for which multiple sustainability concerns have been articulated in the past

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decades (Boyd et al., 2020; Kuempel et al., 2021; Tezzo et al., 2021). Indeed aquatic food systems are not only essential for the food security of hundreds of millions of people globally through the provision of nutritious food (Burbridge and Rosenthal, 2001; Beveridge et al., 2013; Troell et al., 2014; Ishimura et al., 2015; Ceballos et al., 2018; Filipski and Belton, 2018; Gephart et al., 2020), but are also critical in many parts of the world for sustaining economic growth (Costello et al., 2020); Gentry et al., 2017) and supporting job creation and income generation (Ahmed et al., 2009; Beveridge et al., 2013; Béné et al., 2016; Haque and Dey, 2016; Nasr-Allah et al., 2020).

In recent years, scholars have pointed towards the need for data-driven approaches and a solid evidence base about the characteristics and performance of aquatic food systems, as a means of enhancing their short- and long-term sustainability (Engle and D'Abramo, 2016; Engle et al., 2017; Farmery et al., 2021; Mikkelsen et al., 2021). Among others, such information is crucial for informed and transparent decision-making (Bush et al., 2021), not the least to support investments for facilitating the adoption and diffusion of suitable innovation packages (Lasner et al., 2017; Shikuku et al., 2021b) that can catalyze the transitioning to a sustainable, equitable, inclusive and resilient food system (FAO, 2020a, 2020b). However, despite an emerging evidence base about the sustainability impact of aquatic food systems and the factors mediating it (e.g. Naylor et al., 2021; Bohnes and Laurent, 2021; Dam Lam et al., 2022) and the growing generation of relevant statistics mainly by international organizations (e.g. Food and Agricultural Organization), national governments and larger private companies (e.g. DOF, 2018; FAO, 2020a, 2020b), there is limited evidence and lack of comprehensive data about the sustainability performance and trade-offs in aquatic food systems (FAO, 2018;Engle and D'Abramo, 2016). In response to these data gaps, it is imperative to improve data gathering and analysis for aquatic foods at the farm and system levels (FAO, 2016, 2018; FAO, 2020a, 2020b). This includes broad-scale assessments (and related tools) to produce benchmarking information about the performance of aquatic food systems, as a means of informing policy and promoting appropriate technologies and investments to enhance their sustainability.

Such knowledge and data gaps are particularly pronounced in low-income countries due to the combined effect of capacity, funding, and institutional constraints (Gill et al., 2019; Chan et al., 2019). These constraints are not only encountered in extremely poor countries or countries where aquatic food systems play a minor role in the food system but also in developing countries with extensive aquatic food sectors (Blasco et al., 2020). A relevant example is the case of Egypt, where fish production and aquatic food systems play a key role for the food security and nutrition of a large fraction of the population, as well as of the broader economy (FAO, 2020a, 2020b). In particular, the Egyptian aquaculture industry has expanded rapidly in the last two decades, from producing 139,389 tons of farmed fish in 1998 to 1,561,457 tons in 2018 (FAO 2003–2020). This increase was achieved through a paradigm shift from traditional extensive to semi-intensive fish production and modern intensive aquaculture systems supported by the Egyptian government policies and growing private investments (Shaalan et al., 2018; Soliman and Yacout, 2016; Adeleke et al., 2020). As a result, Egypt now ranks as the top aquaculture producer in Africa (accounts for 71% of the continent's output) and a major global aquaculture powerhouse (Shaalan et al., 2018; FAO, 2016). Importantly, Egypt is the third largest tilapia producer globally (after China and Indonesia), with tilapia aquaculture playing a significant role for the national economy and food security (Macfadyen et al., 2012; FAO, 2020a, 2020b; Nasr-Allah et al., 2020), as all the national output is marketed locally (Shaalan et al., 2018).

However, despite this success, the Egyptian tilapia sector faces multiple sustainability challenges. On the one hand, the tilapia aquaculture sector experiences declining profitability and production efficiency due to disease outbreaks, seasonal climate, and sensitive ecosystems (Walker and Winton, 2010; Dickson et al., 2016; Henriksson et al., 2017). On the other hand, globalization, rapid changes in technological and institutional innovations, disease outbreaks, shifts in food supply and demand, climate change, and environmental constraints have rapidly changed the context within which Egyptian tilapia aquaculture farmers have to operate (Adeleke et al., 2021; Kaleem and Bio Singou Sabi, 2021). In this rapidly changing context, there is a real need to understand the sustainability performance of the sector. However, as mentioned above, there is a general lack of robust information about the characteristics, performance, and trade-offs of tilapia farming systems in the country that can inform policy decisions and investors on the requirements to achieve sustainable intensification, and thus how to enhance sustainability. This becomes more imperative considering Egypt's leading status as an aquaculture producer in Africa and globally (FAO, 2020a, 2020b). A better understanding of tilapia systems' performance and the policy/practice implications in Egypt can provide useful insights for other developing countries expanding their aquaculture sectors based on tilapia.

The aim of this study is to characterize the tilapia aquaculture production sector in Egypt and assess its sustainability performance. Analysing primary survey data from 402 aquaculture producers in Kafr El Sheikh governorate, first, we identify the prevalence of different tilapia aquaculture systems in terms of their production characteristics and practices, more notably in terms of pond size, species diversification, and stocking and feeding practices. Second, using a combination of ordinary least square (OLS) regressions and propensity score matching, we identify the factors affecting their adoption and their sustainability outcomes. Building on these empirical findings, we provide policy insights for the sustainable intensification of aquaculture, not only for the Egyptian tilapia aquaculture sector but also for other developing countries across Africa and beyond in their efforts to sustainably intensify their aquaculture production systems. Consequently, with these insights we expand and extend the aquaculture sustainability literature (Little et al., 2010; Haque and Dey, 2016; Engle et al., 2017; Boyd et al., 2020) by providing a benchmark of sustainability performance and pointing to the trade-offs between and within sustainability outcomes.

2. Materials and methods

2.1. *Conceptual framework and research approach*

The conceptual framework guiding our empirical analysis (Fig. 1) draws from the literature on the different dimensions of sustainable food systems (Béné et al., 2019). This literature considers food and nutrition security, economic performance, and environmental impacts as crucial dimensions of sustainable food systems, including of aquatic food systems (Karim et al., 2020; Dam Lam et al., 2022; Jiang et al., 2022; Shamsuddin et al., 2022). Some of these outcomes can be positive and reinforcing, e.g., the simultaneous achievement of higher productivity, profitability, and food security (Chan et al., 2019; Dam Lam et al., 2022). Other impacts can be negative such as the increased pressure on scarce water resources or increased emissions (Jiang et al., 2022; Crawford and Macleod, 2009).

Considering that in aquatic food systems many of these dimensions intersect (Drakeford et al., 2020; Sampantamit et al., 2020), in this study we consider multiple sustainability outcomes for the characterized tilapia systems. Using the available data, we consider a proxy outcome. Accordingly, we assess the performance of tilapia systems on (a) profitability as a measure of economic performance, (b) food consumption score (FCS) as a measure of food security, and (c) freshwater consumption (FWC) and feed conversion ratio (FCR) as measures of environmental impact.

However, several studies have shown that different aquaculture systems can have quite different sustainability outcomes, even within the same geographical context (Dam Lam et al., 2022; Sampantamit et al., 2020; Shamsuddin et al., 2022). In the broadest sense, different aquaculture production systems can have inherently distinct

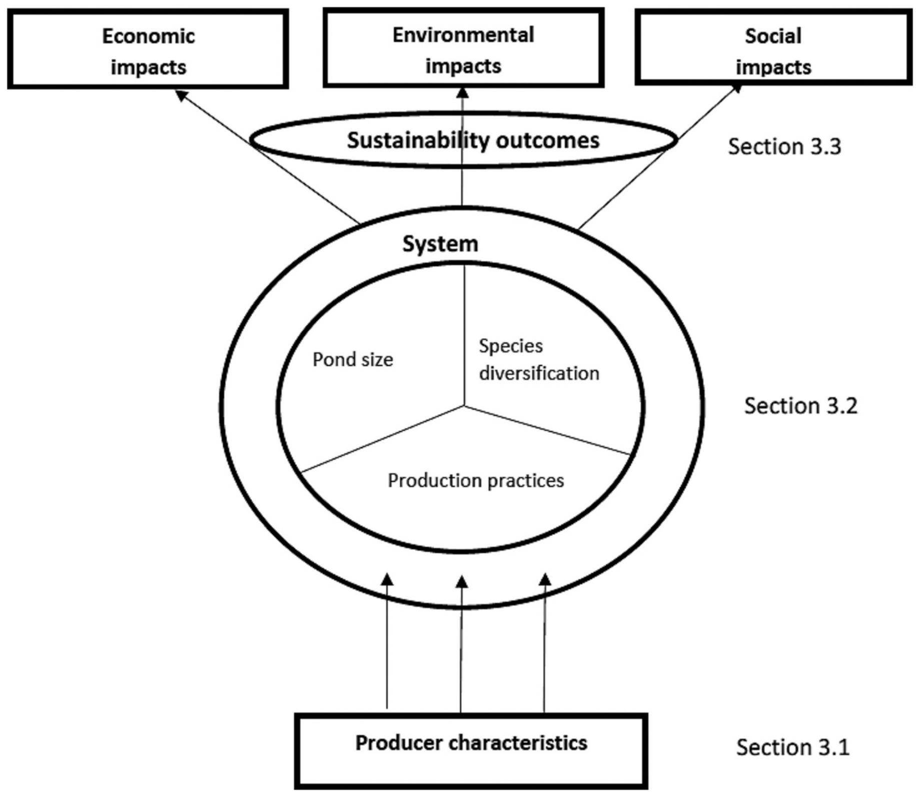

Fig. 1. Conceptual framework of the study.

characteristics and production practices/activities that affects their performance (Karim et al., 2020; Shamsuddin et al., 2022). For example the rich literature about the on-farm performance of aquaculture systems has identified the effect of several such characteristics and production practices/activities such as production scale (e.g. size of ponds), pond preparation practices, diversification (i.e., monoculture or polyculture), stocking practices (e.g., weight at stocking, stocking density), feeding management (e.g., types of feed used), or water quality management (e.g., frequency of water exchange, monitoring levels of dissolved oxygen), among others on economic performance (Nasr-Allah et al., 2020; Tran et al., 2021).

Several studies show that such characteristics and production practices/activities are critical in determining the quantity and quality of harvested fish from ponds and other sustainability outcomes such as generated income and household food security (Nasr-Allah et al., 2020; Tran et al., 2021; Saiful Islam et al., 2015. At the same time, they also dictate the environmental performance of aquaculture systems in terms of water quality, among others (Henriksson et al., 2018; Shepon et al., 2020). When considering the above, in this study we explore how such aquaculture system characteristics and practices/activities intersect with sustainability outcomes in terms of their:

- marginal contribution to sustainability outcomes,
- heterogeneity in contribution to sustainability outcomes,
- and causal effects to sustainability outcomes.

2.2. Study area

In Egypt, fish farms are concentrated in the Lower Delta districts (GAFRD, 2016), with the country's tilapia production concentrated in the four northern governorates of Kafr el Sheikh, Port Said, Sharkia, and Beheira (Murphy et al., 2020). Of these, Kafr El Sheikh is the single most important governorate for fish farming (Macfadyen et al., 2012; Dickson et al., 2016). Official statistics (see Fig. 2) for the last two decades (1998–2018) indicate that production in Kafr El Sheikh on average contributed 47% of annual aquaculture production in the country (GAFRD, 2020).

The governorate was purposively selected to represent diverse tilapia aquaculture production systems. Four districts (Markaz), namely Burullus, El Hamoul, El Ryad, and Sidi Salm (Fig. 3), were purposively selected because of their importance in tilapia aquaculture.

2.3. Data collection

Farm-level data were collected from farm owners and managers, using a pre-tested digital questionnaire that was programmed in Kobo Toolbox for computer assisted personal interviews (CAPI) using mobile phone tablets. The questionnaire was meant to collect data related to respondent demographics, tilapia yields, inputs, revenue, expenses, management practices, food security and diets, among others. A total of 402 respondents from tilapia farming households in Kafr El Sheikh governorate (Fig. 3) participated in the survey in September–December 2019. The sampling frame comprised tilapia aquaculture producers. In the first stage, four districts, namely Burullus, Hamoul, Ryad, and Sidi (Fig. 1) were selected for the study. Within each district, three separate lists of tilapia fish farmers were compiled from GAFRD database and stratified by different aquaculture farm sizes. In this case, three distinct groups of farms (with <4.2 ha, 4.2–10 ha and larger than 10 ha) were found to reflect differences in their production scale.[1] Small scale farms were viewed as farms <4.2 ha, medium scale farms as those with aquaculture farm size from 4.2 to 10 ha, while large scale farms were classified as those with aquaculture farm size larger than 10 ha. These

[1] Scale of operation in aquaculture vary from country to country, and between aquaculture farming systems, and it embraces different criteria of categorization of which the common indicator is farm size (FAO, 2013; Phillips et al., 2015). Farm size is often positively associated with volume of production of production and the number of factors of production used.

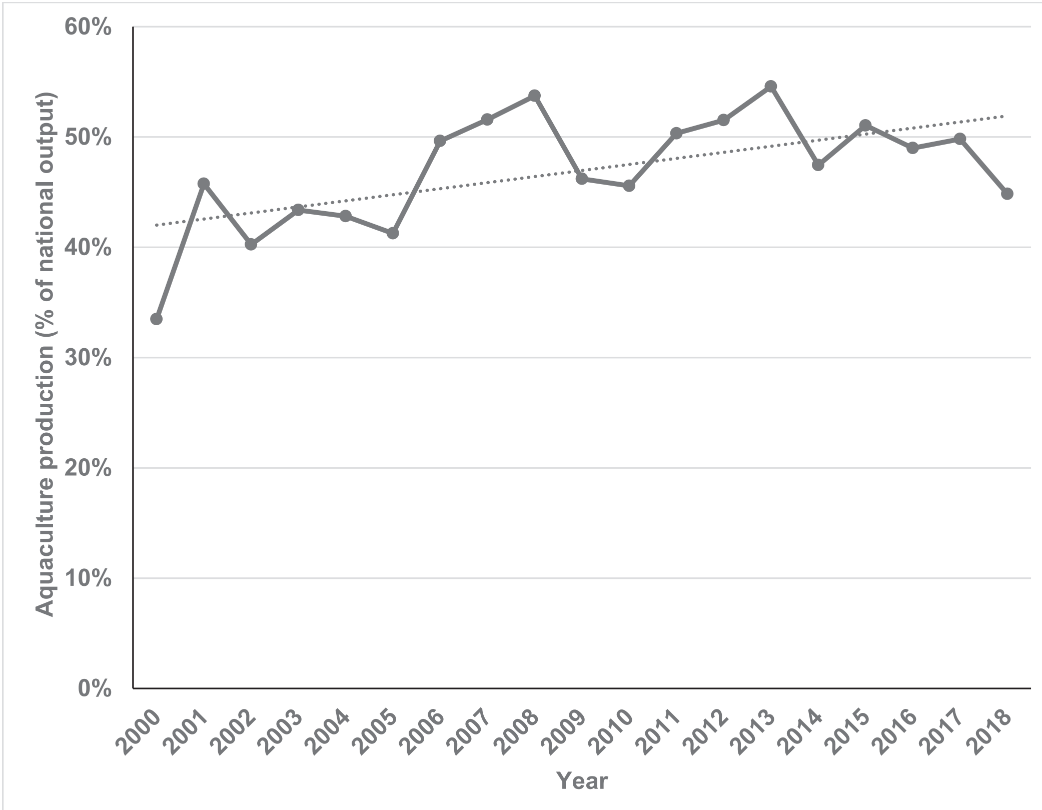

Fig. 2. Aquaculture production in Kafr El Sheikh governorate (in % of total national output).

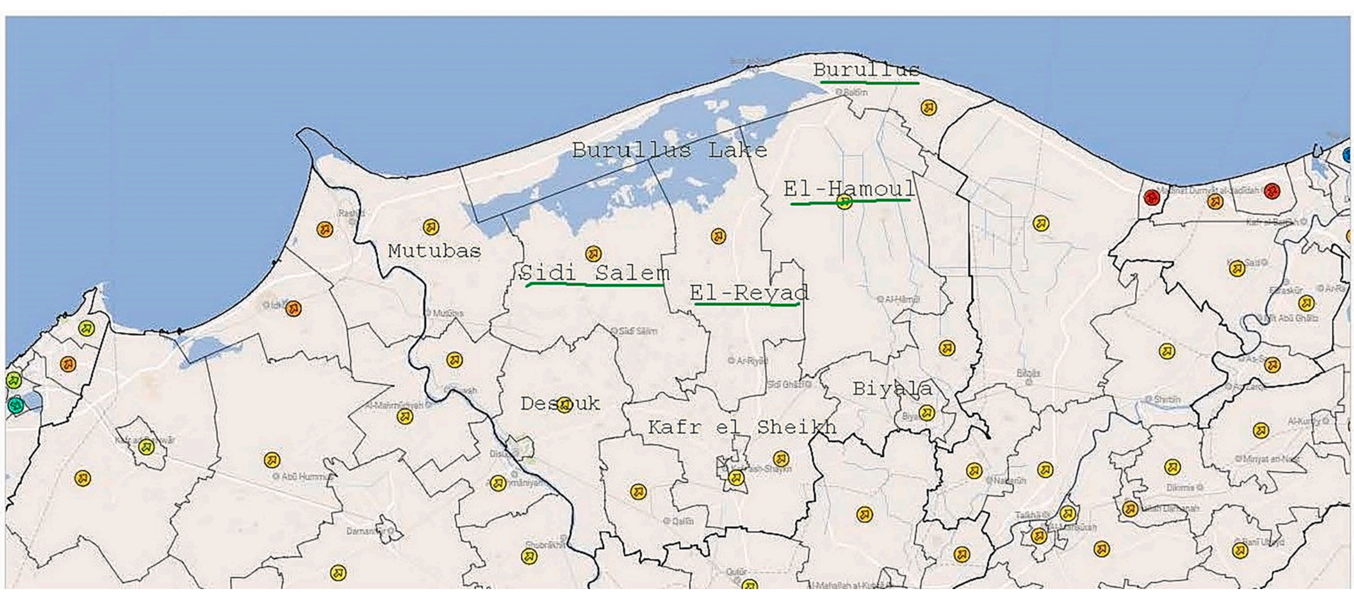

Fig. 3. Map of Kafr El Sheikh Governorate.
Note: Underlined are the names of the districts selected for the study.

three categories of farms represent a continuum of small-scale to medium and large-scale aquaculture production in Egypt (GAFRD, 2018) and also captures the different farm sizes found by previous studies (Dickson et al., 2016; Hebicha et al., 2013; Macfadyen et al., 2012).. Some districts had more tilapia aquaculture producers than others while within a district, the proportions of small, medium, and large-scale farmers may be skewed. Therefore, probability proportionate-to-size sampling was used to randomly select 402 tilapia aquaculture farmers between the four districts (Burullus = 44, El Hamoul = 96, El Ryad =170, and Sidi = 92).

Data were collected by thoroughly trained enumerators under close supervision. These enumerators were trained on the content of the questionnaire and on how to collect data using mobile tablets in a real setting. In order to ensure the collection of quality data, a quality check mechanism was established where at the end of each survey enumerators uploaded the data to the central server and a research analyst checked for potential mistakes and inconsistencies. More details of the data and the data collection process is explained in Shikuku et al. (2021a).

2.4. Data analysis

2.4.1. Estimation of main study variables

2.4.1.1. Sustainability outcomes. In this study we consider profitability in the form of gross margins of tilapia aquaculture production systems to reflect on the economic performance sustainability outcome. Accordingly, gross margins were calculated as total gross fish revenue less total variable costs. The inputs included in the calculation of variable cost are seed, feed, labor, fertilizer, and chemicals (e.g., water treatment chemicals). The cost of inputs was measured in USD ha^{-1} per cycle using the World Bank's 2019 official exchange rate for Egypt (US\$1 = EGP17.06). Feed costs included the costs of both pelleted and extruded feed. Labor cost was calculated by considering three types of labor, namely family, hired part-time, and hired full-time. For each type of labor, male and female person-days were computed. Cost for hired labor was obtained by multiplying the total number of person days by the median daily wage for the specific type of labor. We further included other costs, such as renting of land, electricity, ice, transportation, fuel, and miscellaneous expenses, such as cost of ropes, tubes, batteries, and torches. In addition, we computed the benefit-cost ratio as total revenue divided by total variable cost.

The second sustainability outcome variable is the FCS, which is a proxy of food security. The FCS is a measure of dietary diversity and is based on the recall of the distinct types of food consumed within a household in the previous 7 days (World Food Programme, 2008). Food items were grouped into seven specific food groups. All consumption frequencies of food items of the same group were then summed, and values of each group above seven were recoded to seven. For each food group, the value obtained was then multiplied by its weight to create weighted food group scores. Summing these scores produced the FCS. Previous studies have shown that FCS correlates well with other indicators of food security, and this indicator has been used in several studies to understand the level of household food insecurity between and within regions (Dam Lam et al., 2022; Khanum et al., 2022).

The remaining two sustainability outcomes relate to the environment dimension. The first one is FWC, which is consistent with existing literature (e.g., Henriksson et al., 2017) and is calculated as:

$$FWC = (evaporation\ rate\ x\ total\ pond\ area\ x\ length\ of\ cycle)$$

Whereas Henriksson et al. (2017) calculated FWC rate using temperature, humidity and windspeed ranges from the Nile River delta, in this study we asked farmers about their water exchange/addition rate (meter/time) as a proxy for FWC. We use responses to this question to construct a proxy for evaporation rate. The second outcome is the FCR measured by dividing the total quantity of feed (kg) by the quantity of harvested fish (kg). We use this as a proxy of different environmental impacts, as feed is the main driver behind global warming, eutrophication, and other impacts (Henriksson et al., 2017).

2.4.1.2. Treatment variables. The treatment variables reflect different activities involved in aquaculture production. First, we measure *survival rate* as the number of tilapia harvested divided by the number of tilapia stocked. The resulting number was multiplied by one hundred to express as a percentage. Second, we measure *stocking density* (number of fingerlings stocked per square meter). Using this variable, we create three dummy variables for stocking densities: (a) 0.24–2.98 fingerlings m^{-2}; (b) 3.02–3.57 fingerlings m^{-2}; and (c) 3.67–7.14 fingerlings m^{-2}. Third, based on *weight at stocking*, we construct four dummy variables: (a) weight at stocking <0.25 g; (b) weight at stocking = (0.3 g–0.5 g); (c) weight at stocking = (0.75 g–3 g); and (d) weight at stocking >4 g. Fourth we consider *feed use*. Three dummy variables were constructed: (a) pellet feed only; (b) extruded feed only; and (c) both pellet and extruded feed. Finally, we consider *type of culture system* and construct a dummy variable equal to one if the farmer practiced polyculture and zero if otherwise.

2.4.2. Ordinary least squares regressions and simultaneous quantile regressions

We start our empirical analysis by estimating ordinary least squares (OLS) regression to assess the marginal contribution of each treatment variable on the four outcome variables. We assessed for heteroscedasticity using both the White test and Breusch-Pagan test which tests the null hypothesis that standard errors are homoscedastic. OLS was estimated with heteroscedasticity-robust standard errors. Such standard errors are asymptotically valid in the presence of any kind of heteroscedasticity (Wooldridge, 2002).

We further test for multicollinearity by examining the variance inflation factor (VIF). A VIF >10 can be interpreted as an indicator of exceedingly high correlation among the variables that the standard error of the regression coefficient is excessively inflated, and the coefficient is likely to be poorly estimated (Maddala and Lahiri, 1992). Finally, we tested whether the functional form of our model was adequate. Specifically, we tested the null hypothesis that non-linear restrictions in the explanatory variables do not significantly explain the dependent variables.

Aquaculture systems and practices are likely to influence economic, social, and environmental outcomes differently depending on the level of the outcomes. While OLS estimates are useful to show marginal contributions of aquaculture systems, there might be major differences at various levels of the economic, food security, and environmental outcomes, see for example, Shikuku et al. (2017) in the context of climate change adaptation. Therefore, we estimate simultaneous quantile regression to assess marginal contribution of aquaculture systems at different levels of outcome variables. For all indicators except FCS, the quantiles are: 0.25, 0.50, and 0.75. The quantiles for FCS are 0.10, 0.60, and 0.90.

2.4.3. Propensity score matching

Although the OLS is useful to descriptively assess the marginal contribution of tilapia aquaculture systems, self-selection implies that parameter estimates will be biased unless unobserved heterogeneity is controlled for. In this study, we use propensity score matching (PSM) to estimate the causal effects of the tilapia aquaculture systems and practices.

Here we estimated the average treatment effect on the treated (ATT), defined as the average difference in outcomes of aquaculture farming households, with and without implementing a particular system type (Takahashi and Barrett, 2014):

$$\begin{aligned} \text{ATT} &= E\{Y_{iA} - Y_{iN} | T_i = 1\} \\ \text{ATT} &= E(Y_{iA} | T_i = 1) - E(Y_{iN} | T_i = 1) \end{aligned} \quad (1)$$

where $E\{\bullet\}$ is the expectation operator, Y_{iA} is the potential outcome under adoption of a culture system or farming practice while Y_{iN} is the potential outcome under no adoption of the system or practice and T_i is the treatment indicator, equal to one if the household used a particular culture system or farming practice and zero if otherwise. The challenge in Eq. (1) is that it is not possible to observe, for the same adopter household i, the counterfactual outcome, $E(Y_{iN}|T_i = 1)$, (that is, the potential outcome had the household not adopted). Replacing the unobserved counterfactuals with the outcomes of non-adopters, $E(Y_{iN}|T_i = 0)$, may result in biased ATT estimates (Angrist and Pischke, 2019).

In this study, PSM was used to avoid the problem described above. PSM assumes that sample selection bias can be eliminated by conditioning on observable variables. This is achieved by matching each adopter household with one or more non-adopter households with similar observable characteristics. Therefore, matching models simulate the conditions of an experiment in which adopters of a particular culture system or farming practice and non-adopter households are randomly assigned, allowing for the identification of a causal link between culture system or farming practice choice and measures of performance. Two assumptions are crucial when applying PSM, namely unconfoundedness assumption also referred to as conditional independence assumption (CIA) and common support assumption (CSA). The CIA implies that once a vector of observable characteristics is controlled for, adoption of a culture system or farming practice will be random and uncorrelated with the economic, social, and environmental outcome variables. The propensity score under the CIA is given by:

$$p(W) = pr(T = 1|X) = E(T|X) \quad (2)$$

where $T = 1$ or 0 is the indicator for adoption of a system or otherwise, and X is the vector of observable characteristics. The conditional distribution of W, given $p(X)$, is similar in both groups of adopter and non-adopter households. On the other hand, the CSA helps in ensuring that every individual has a positive probability of being either an adopter or a non-adopter, hence ruling out perfect predictability. The CSA is expressed as:

$$0 < pr(T = 1|X) < 1 \quad (3)$$

Under the assumptions (2) and (3), the ATT can be expressed as follows:

$$\text{ATT} = E[E\{Y_{iA}|T_i = 1,p(X)\} - E\{Y_{iN}|T_i = 0,p(X)\}|T = 1] \quad (4)$$

One of the weaknesses of the PSM method is that it does not capture selection bias based on unobserved heterogeneity. However, Rosenbaum bounds sensitivity analysis can check if the PSM results are sensitive to hidden bias (Becker and Ichino, 2002).

The PSM approach as applied in this study followed two steps. The first step involved estimation of the propensity scores or the conditional probability of a system type or aquaculture practice using a probit model. In the second step, adopters and non-adopters were matched by their estimated propensity scores using the nearest neighbor matching algorithm. Nearest neighbor matching matches a subject from the control group to a subject in the treatment group, based on the closest propensity score.[2]

Propensity score matching helps to balance the distribution of observed covariates (Lee, 2013), meaning there should be no systematic differences in the distribution and overlap of covariates between adopter and non-adopter households after matching (Gitonga et al., 2013). The quality of matching can, therefore, be tested using covariates balancing tests (Rosenbaum and Rubin, 1985; Sianesi, 2001). Specifically, the equality of means of observed characteristics in the adopter and non-adopter groups after matching was examined using a two-sample t-test: after matching, there should be no significant differences (Gitonga et al., 2013). Further, the matching was tested by comparing the pseudo R^2 and p-values of the likelihood ratio test of the joint insignificance of all the regressors obtained from the probit analysis before and after matching the samples. The pseudo-R^2 should be lower, and the joint significance of covariates should be rejected (Kassie et al., 2011). Finally, propensity score graphs were used to check visually if the common support condition was satisfied, that is, if there was sufficient overlap. In addition, the balancing property was checked using mean absolute standardized bias (MASB) between adopters and non-adopters as suggested by Rosenbaum and Rubin (1985); a standardized difference >20% should be considered too large and an indicator that the matching process has failed. The PSM estimation is not robust in the presence of hidden bias arising from unobserved confounders that simultaneously affect assignment to both the treatment and the outcome variable.. Using the Rosenbaum (2002) bounds test, we checked the sensitivity of the estimated average adoption effects to hidden bias.

The observable covariates considered, i.e. factors that were likely to affect the probability of adopting a culture system or practice, were selected based on previous adoption and impact studies, studies on performance assessment of aquaculture systems, and economic theory, and included farmer and household characteristics (age, education, assets index, number of household members involved in aquaculture, whether aquaculture is the main source of livelihoods for the household, farmer's experience in tilapia farming, access to information, access to credit, and risk attitude).

3. Results

3.1. Descriptive statistics

Table 1 contains the descriptive summary statistics of the study respondents. The average respondent age was 44 years. Approximately, 58% of the respondents had completed secondary education or above, 28% completed primary or preparatory education, while 14% had no formal education. The respondents were overwhelmingly male (99%) and 84% were the owners of the farms used for aquaculture. On average the respondents had practiced fish farming for 17 years, indicating substantial experience. Our sample respondents are risk-neutral, on average. Polyculture in earthen ponds was the dominant culture system; more than four-fifths of our sample respondents practiced tilapia-mullet polyculture. Corresponding previous studies, we found that all farmers were practicing monosex tilapia production. The main farmed species in the study area were *Oreochromis niloticus* and Abassa Strain of Nile Tilapia (improved strain). Access to weather information and credit was incredibly low. Furthermore, very few farmers participated in farmer groups. The average size of land under aquaculture was 5.4 ha.

Table 1
Characteristics of study respondents.

Variable	Description	Mean / proportion
Age	Age of the respondent (years)	44.31 (11.02)
No formal education	1 = farmer has no formal education; 0 = otherwise	0.14 (0.34)
Primary education	1 = farmer has primary education; 0 = otherwise	0.15 (0.36)
Preparatory education	1 = farmer has preparatory education; 0 = otherwise	0.13 (0.34)
Secondary education	1 = farmer has secondary education; 0 = otherwise	0.45 (0.50)
Tertiary education	1 = farmer has tertiary education; 0 = otherwise	0.13 (0.34)
Sex	Sex of the respondent (1 = male; 0 = female)	0.99
Manager	Role of the respondent on the farm (1 = owner; 0 = manager)	0.84 (0.37)
Experience	Respondents experience in fish farming (years)	17.52 (9.36)
Polyculture	1 = farmer practices polyculture; 0 = otherwise	0.82
Risk	Farmer's attitude towards risk (score)	4.94 (1.87)
Weather	1 = farmer had access to weather information; 0 = otherwise	0.05 (0.21)
Credit	1 = farmer had access to credit; 0 = otherwise	0.01 (0.11)
Group	1 = farmer participated in a farmers' association; 0 = otherwise	0.08 (0.27)
Farm size	Size of land under aquaculture (acre)	5.39 (4.45)

Notes: Standard deviations in parentheses.

[2] We also conducted robustness checks in which we used two other matching algorithms, namely kernel-based matching and radius matching. Our results remain robust to different matching algorithms. Results of the other matching algorithms are available from the authors upon request.

3.2. Production characteristics of tilapia systems

Table 2 presents results comparing tilapia monoculture and polyculture systems and across different sizes of farms. Stocking density for tilapia under monoculture (3.9 fingerlings m^{-2}) is significantly (p-value <0.01) higher (15%) than in polyculture systems (3.4 fingerlings m^{-2}). However, farmers practicing monoculture stocked significantly (p-value <0.05) smaller-sized fingerlings (1.5 g) compared to their counterparts practicing polyculture systems (2.5 g). Tilapia yields were 20% higher under monoculture (10.5 t ha^{-1} per cycle) than polyculture system (8.4 t ha^{-1} per cycle). Results show that the differences in stocking density, survival rate, and yield of tilapia are not statistically significant across different pond size categories.

3.3. Sustainability outcomes of tilapia aquaculture systems

3.3.1. Ordinary least squares (OLS) regression estimates

Table 3 presents results of OLS regression to characterize tilapia aquaculture systems by assessing their relationship with economic, social, and environmental aspects. Using both the White and Breusch-Pagan test, there was enough evidence to reject the null hypothesis of homoscedasticity at 1% level of significance, supporting our decision to estimate OLS with heteroscedasticity-robust standard errors. All variables had low VIF values (1.03–9.82), indicating absence of multicollinearity. Hence, there was no sufficient evidence to reject the null hypothesis that non-linear restrictions in explanatory variables did not significantly explain the dependent variables.

OLS regression estimates show a positive and significant correlation between survival rate and profitability. There was a weakly significant positive correlation between higher stocking density (3.67–7.14 fingerlings m^{-2}) and profitability (p-value <0.1). However, stocking of larger-sized fingerlings ($>$ 0.3 g) relative to smaller-sized fingerlings ($<$ 0.3 g) had a negative relationship with gross margins (p-value <0.001). Expenditure on pellet and extruded feed, both in isolation and combination, is associated with a reduction in aquaculture profitability (p-value <0.001). Similarly, expenditure on other inputs particularly aquaculture chemicals correlated negatively with profitability (p-value <0.01). Farmers using improved strains and stocking recommended size of fingerlings experienced higher profitability than non-adopters.

Aquaculture polyculture systems were positively associated with higher food security (Food Consumption Score) (though not significant). Both survival rate and stocking density (3.67–7.14 fingerlings m^{-2}) had a positive and significant relationship with FCS. Large-scale farmers experienced higher positive significant relationship than their small-scale farmer counterparts. There was a positive and significant relationship between FCS and stocking larger-sized fingerlings, growing improved strains, and using improved fish feeding methods.

In terms of environmental factors, we found a positive and significant relationship between survival rates and FWC. Survival rate was also negatively associated with FCR. Results further reveal that, compared with farmers stocking 0.24–2.98 fingerlings m^{-2}, those stocking more than three fingerlings m^{-2} (i.e., 3.02–3.57 and 3.67–7.14) had higher FWC. We found a positive significant correlation between FWC and weight of tilapia seed at stocking. Specifically, we found that relative to farmers stocking fingerlings of weight 0.3 g, those using fingerlings between 0.3 g–0.5 g had higher FWC. Stocking fingerlings between 0.75 g–3 g and those with weight above 4 g had a negative and positive relationship with FWC, respectively(though not statistically significant). Use of pellet and extruded feeds, both in isolation and combination, positively correlated with increased FCR suggesting low feed use efficiency. The use of pelleted feed, however, had a negative significant relationship with FWC, implying that the farmers using pelleted feed experience low freshwater consumption. Further, we found that compared with monoculture practice, polyculture aquaculture systems had a positive significant relationship with feed conversion ratio. However, FCR was lower among medium scale (4.2 ha–10 ha) farmers compared to small scale (<4.2 ha) farmers ($p < 0.05$). Results also show that farmers stocking recommended size of fingerlings had higher FWC ($p < 0.01$) but observe lower FCR ($p < 0.05$) compared to their counterparts.

3.3.2. Simultaneous quantile regression estimates

Table 4 contains the estimates of the simultaneous quantile regression model to assess marginal contributions at different levels of the relevant outcomes. First, looking at economic performance, we found consistent results at all different levels. At the lowest quantile, we found that survival rate, stocking density (3.67–7.14 fingerlings m^{-2}), application of fertilizer, and stocking of recommended size of fingerlings correlated with increased gross margins. However, farmers who had stocked fingerlings of weight >0.3 g, used pellet and extruded feed (in isolation and combination), and used chemicals had reduced profitability. At the medium quantile, we found a positive association between gross margins and survival rate, polyculture, and adoption of improved fish health management practices. However, there was a negative relationship between gross margins and stocking of fingerlings of weight >0.3 g, use of pellet and extruded feed (in isolation and combination), and use of chemicals. At the highest quantile, we found a positive correlation between adoption of improved health management practices and gross margins. However, we observed a negative association between gross margins and stocking of fingerlings of weight >0.3 g, use of extruded feed (in isolation and combination with pellet feed), and use of chemicals.

Turning to food security, we found that adoption of improved strains and practicing improved fish feeding correlated with increased food security whereas use of pellet feed only correlated with reduced food security at the lowest quantile. We found a positive relationship between

Table 2
Stocking and yield of tilapia, by species diversification and pond size.

Variable	Species diversification			Size of pond (ha)			
	Monoculture	Polyculture	p-value	<4.2	4.2–10	>10	p-value
Stocking density	3.9	3.4	0.001	3.5	3.4	3.8	0.134
(pieces m^{-2})	(1.2)	(1.0)		(1.1)	(1.0)	(1.2)	
Weight at stocking	1.5	2.5	0.014	2.1	2.8	2.1	0.289
(g)	(3.0)	(4.0)		(3.6)	(4.5)	(3.8)	
Weight at harvesting (g)	339.9	322.3	0.141	323.7	326.6	333.1	0.817
	(91.0)	(97.0)		(93.4)	(99.2)	(103.6)	
Survival rate	79.7	78.4	0.625	79.6	77.5	76.5	0.439
(%)	(19.9)	(18.4)		(17.7)	(19.9)	(20.8)	
Yield	10,460.5	8404.7	0.000	8969.4	8272.7	8963.1	0.126
(Kg ha^{-1} per cycle)	(3230.1)	(2852.6)		(3175.6)	(2777.0)	(2695.7)	
Number of observations	74	328		247	107	48	

Notes: In parentheses are standard deviations. For analysis by culture system, p-value is a t-test of difference in means. For analysis by size of pond, p-values are results analysis of variance (ANOVA).

Table 3
OLS regression estimates of the effect of different tilapia production activities on sustainability outcomes.

	Gross margins (USD/kg tilapia)		Food Consumption Score		Fresh water consumption		Feed Conversion Ratio	
	Coefficient	*p*-value	Coefficient	*p*-value	Coefficient	*p*-value	Coefficient	*p*-value
Survival rate	0.21** (0.09)	0.021	3.82*** (1.68)	0.023	5.80 (1.70)	0.001***	−0.19 (0.05)	0.001***
Stocking density (3.02–3.57 fingerlings m^{-2})	0.04 (0.12)	0.719	−0.98 (2.02)	0.627	3.33 (1.57)	0.035**		
Stocking density (3.67–7.14 fingerlings m^{-2})	0.19* (0.11)	0.083	4.48*** (2.36)	0.058	9.86 (2.74)	0.000***		
Size of fingerlings (0.3–0.5 g)	−0.27*** (0.09)	0.003	12.65*** (1.77)	0.000	5.25 (1.99)	0.009***		
Size of fingerlings (0.75–3 g)	−0.93*** (0.19)	0.000	14.36*** (3.46)	0.000	−1.80 (1.89)	0.342		
Size of fingerlings (>4 g)	−0.06 (0.18)	0.747	14.60*** (2.69)	0.000	2.18 (2.70)	0.421		
Medium body mass							−0.14 (0.05)	0.004***
Highest body mass							−0.00 (0.07)	0.990
Feed type = pellet only	−0.61*** (0.22)	0.005	−7.37 (6.67)	0.270	−4.71 (2.77)	0.090*	1.02 (0.32)	0.002***
Feed type = extruded only	−0.67*** (0.15)	0.000	−2.00 (4.72)	0.673	0.57 (2.48)	0.819	0.90 (0.28)	0.001***
Feed type = both pellet & extruded only	−0.74*** (0.25)	0.003	0.94 (5.46)	0.863	2.76 (2.89)	0.341	0.97 (0.30)	0.001***
Polyculture	−0.09 (0.11)	0.429	2.17 (2.26)	0.336	0.32 (2.29)	0.889	0.23 (0.04)	0.000***
Applies chemicals	−0.56*** (0.18)	0.002	−0.03 (2.95)	0.991	0.36 (2.16)	0.870	0.19 (0.13)	0.154
Applies fertilizer	0.10 (0.12)	0.375	0.93 (1.95)	0.634	−0.22 (1.64)	0.892	0.01 (0.06)	0.869
Medium scale farmer (4.2–10 ha)	0.04 (0.11)	0.681	2.54 (1.79)	0.156			−0.14 (0.06)	0.027**
Large scale farmer (>10 ha)	−0.03 (0.17)	0.869	6.78** (2.98)	0.023			−0.04 (0.09)	0.636
Improved strains	0.36*** (0.12)	0.004	14.57*** (3.88)	0.000	0.11 (2.64)	0.966	−0.11 (0.09)	0.221
Recommended size of fingerlings	0.53* (0.30)	0.073	−2.49 (4.93)	0.614	27.32 (4.81)	0.000***	−0.49 (0.22)	0.027**
Improved feeding	−0.21 (0.21)	0.315	21.21*** (3.95)	0.000	−1.61 (3.33)	0.629	−0.03 (0.14)	0.821
Improved water management	−0.05 (0.22)	0.814	2.55 (12.73)	0.842	6.95 (10.16)	0.495	−0.11 (0.21)	0.589
Improved fish health management	0.03 (0.32)	0.916	−8.52 (5.44)	0.118	−36.51 (3.36)	0.000***	0.01 (0.22)	0.947
Cost kg^{-1} tilapia			−0.79 (1.82)	0.665				
Gross margins kg^{-1} tilapia			0.61 (1.53)	0.689				
Constant	1.35 (0.20)	0.000	26.33 (6.26)	0.000	0.15 (3.95)	0.970	0.48 (0.29)	0.094**
Observations	402		402		322		402	
Pseudo R-squared	0.18		0.30		0.15		0.16	

FCS and stocking density (3.67–7.14 fingerlings m^{-2}), stocking fingerlings at weight >0.3 g, adoption of improved strains and practicing improved fish feeding at both the medium and highest quantiles. Survival rate and practicing large scale farming also correlated with improved food security at the middle quantile. At the highest quantile, farmers who reported to have practiced stocking of recommended size of fingerlings and those using improved fish health management had lower FCS compared to non-adopters.

Results show heterogeneity in the correlation between tilapia aquaculture systems and environmental outcomes at the different quantiles. FWC correlated positively with stocking density (3.67–7.14 fingerlings m^{-2}) and use of recommended size of fingerlings at all quantiles. Stocking at the density of 3.02–3.57 fingerlings m^{-2} was associated with increased FWC at the middle and highest quantiles. Stocking fingerlings of size 0.3 g–0.5 g and adoption of improved water management correlated with increased FWC at the highest quantile while there was a positive relationship between adoption of improved strains and FWC at the lowest quantile. However, adoption of improved fish health management practices correlated with reduced FWC at all quantiles while use of fingerlings of weight 0.75 g–3 g was associated with reduced FWC at the middle and highest quantiles. We find a negative correlation between survival rate and FCR at all quantiles. At the lowest and middle quantiles, there was a negative relationship between FCR and medium scale farming whereas large scale farming and improved fish feeding correlated with reduced FCR at the lowest quantile. However, use of pellet and extruded feed (in isolation and combination) correlated with increased FCR at the lowest and middle quantiles. Similarly, we found that polyculture systems are associated with increased FCR at the middle and highest quantiles.

3.3.3. *Propensity score matching estimates*

Confounding factors and unobserved heterogeneity mean that there might be systematic differences between adopters and non-adopters of tilapia aquaculture systems and practices. Failure to control for selection

Table 4
Simultaneous quantile regression estimates of the marginal contribution of different tilapia systems on sustainability outcomes.

	Gross margins (USD/kg tilapia)			Food Consumption Score			Freshwater Consumption			Feed Conversion Ratio		
	25%	50%	75%	10%	60%	90%	25%	50%	75%	25%	50%	75%
Survival rate	0.23**	0.13**	0.03	−1.21	3.64*	4.86	0.83	1.36	1.71	−0.06**	−0.09**	−0.18***
	(0.12)	(0.06)	(0.06)	(1.58)	(2.09)	(3.53)	(0.81)	(0.90)	(1.09)	(0.03)	(0.04)	(0.05)
Stocking density (3.02–3.57 fingerlings m^{-2})	−0.02	−0.02	0.00	1.98	−2.14	−0.29	0.92	2.64**	4.69***			
	(0.12)	(0.07)	(0.09)	(2.15)	(2.28)	(3.68)	(0.77)	(1.19)	(1.23)			
Stocking density (3.67–7.14 fingerlings m^{-2})	0.22**	0.08	0.07	1.41	5.45*	8.57**	2.16**	4.71***	6.40**			
	(0.10)	(0.06)	(0.08)	(2.21)	(2.92)	(3.85)	(1.07)	(1.07)	(3.08)			
Size of fingerlings (0.3–0.5 g)	−0.27***	−0.19***	−0.17**	0.62	15.08***	24.52***	0.70	0.57	3.43*			
	(0.10)	(0.07)	(0.08)	(1.97)	(2.60)	(3.75)	(1.17)	(1.24)	(1.76)			
Size of fingerlings (0.75–3 g)	−1.03***	−0.67***	−0.54***	−0.09	17.22***	26.79***	−1.88	−3.44**	−3.14*			
	(0.39)	(0.21)	(0.12)	(2.48)	(5.58)	(8.08)	(1.38)	(1.48)	(1.64)			
Size of fingerlings (>4 g)	−0.07	−0.08	0.09	1.87	14.92***	32.11***	−0.79	−1.45	2.02			
	(0.15)	(0.08)	(0.09)	(2.97)	(4.01)	(7.06)	(1.11)	(1.61)	(1.74)			
Medium body mass										−0.08**	−0.05	−0.10*
										(0.03)	(0.04)	(0.05)
Highest body mass										−0.06*	0.01	−0.07
										(0.03)	(0.04)	(0.06)
Feed type = pellet only	−1.00***	−0.52*	−0.38	−21.60*	−4.49	−4.48	−2.56	−3.22	−6.87*	1.08**	1.35**	0.35
	(0.22)	(0.26)	(0.23)	(12.05)	(6.74)	(6.78)	(3.30)	(3.32)	(3.91)	(0.42)	(0.64)	(0.75)
Feed type = extruded only	−0.72***	−0.44***	−0.39***	−1.76	−5.97	0.26	−1.81	−0.97	−0.83	1.25***	1.19**	0.26
	(0.17)	(0.14)	(0.14)	(3.67)	(4.46)	(6.34)	(2.99)	(3.20)	(3.42)	(0.37)	(0.60)	(0.65)
Feed type = both pellet & extruded only	−0.72**	−0.44**	−0.39**	3.73	−2.08	−3.64	0.26	2.11	3.14	1.30***	1.22**	0.24
	(0.30)	(0.18)	(0.19)	(5.39)	(5.85)	(8.06)	(3.13)	(3.44)	(3.95)	(0.38)	(0.60)	(0.66)
Polyculture	−0.01	0.15***	0.11	2.81	−0.31	−3.72	1.14	0.26	−0.46	0.06	0.12***	0.18***
	(0.09)	(0.05)	(0.07)	(1.83)	(3.07)	(3.68)	(1.25)	(1.38)	(1.62)	(0.04)	(0.03)	(0.05)
Applies chemicals	−0.67**	−0.35*	−0.24**	0.05	−1.36	1.12	−0.33	1.25	2.22	0.02	−0.00	0.00
	(0.31)	(0.18)	(0.11)	(3.02)	(4.81)	(5.03)	(1.51)	(1.82)	(2.39)	(0.04)	(0.05)	(0.09)
Applies fertilizer	0.26**	0.09	0.06	−0.64	0.53	−1.00	0.72	0.82	0.02	0.05	0.02	−0.03
	(0.12)	(0.07)	(0.07)	(1.53)	(2.34)	(3.36)	(0.95)	(1.19)	(1.23)	(0.04)	(0.03)	(0.04)
Medium scale farmer (4.2–10 ha)	−0.10	0.08	0.03	0.48	2.56	0.52				−0.05*	−0.08**	−0.08
	(0.14)	(0.07)	(0.07)	(1.38)	(2.67)	(3.85)				(0.03)	(0.04)	(0.05)
Large scale farmer (>10 ha)	−0.52	−0.04	0.08	1.31	7.88**	9.49				−0.10**	−0.08	0.00
	(0.33)	(0.17)	(0.12)	(1.31)	(3.78)	(6.19)				(0.04)	(0.07)	(0.10)
Improved strains	0.30	0.12	0.01	22.80***	10.62**	18.87*	4.44***	2.82	−1.01	−0.10	−0.08	−0.12
	(0.26)	(0.15)	(0.18)	(3.91)	(5.02)	(11.15)	(1.43)	(2.27)	(2.69)	(0.13)	(0.13)	(0.16)
Recommended size of fingerlings	1.42**	0.24	0.01	9.46	0.61	−22.62**	35.79***	33.27***	31.13***	−0.11	−0.16	−0.44
	(0.56)	(0.36)	(0.28)	(12.26)	(7.04)	(10.60)	(3.11)	(4.17)	(8.01)	(0.21)	(0.25)	(0.28)
Improved feeding	−0.64*	−0.32	−0.17	25.73**	21.04***	21.38***	1.93	−0.08	−0.90	−0.20**	0.04	0.14
	(0.37)	(0.28)	(0.20)	(11.74)	(4.74)	(7.43)	(2.41)	(3.05)	(7.01)	(0.09)	(0.15)	(0.16)
Improved water management	−0.51	−0.26	0.02	−3.62	−3.33	14.47	3.18	−0.97	25.73*	−0.43	−0.13	0.15
	(0.40)	(0.31)	(0.32)	(18.26)	(18.96)	(22.14)	(15.97)	(16.55)	(15.15)	(0.29)	(0.31)	(0.26)
Improved fish health management	−0.18	0.70**	0.59**	−14.40**	−14.11	−23.85*	−41.34***	−40.12***	−39.51***	−0.01	−0.38	−0.30
	(0.57)	(0.31)	(0.25)	(6.26)	(8.77)	(12.27)	(2.31)	(2.49)	(3.33)	(0.21)	(0.23)	(0.26)
				−47.41	−0.18	5.94						
				(1.66)	(3.06)	(4.44)						
				0.30	−0.42	7.17						
				(1.26)	(2.46)	(4.51)						
Constant	1.19	1.13	1.37	22.57	34.45	25.89	3.26	4.94	6.44	−0.00	0.14	1.30*
	(0.25)	(0.17)	(0.16)	(4.78)	(7.64)	(11.85)	(3.30)	(4.01)	(4.56)	(0.37)	(0.61)	(0.67)
Observations	402	402	402	402	402	402	322	322	322	402	402	402
Pseudo R-squared	0.18	0.11	0.08	0.13	0.25	0.26	0.05	0.08	0.11	0.13	0.07	0.07

bias will generate biased estimates. We controlled for selection bias using PSM which generates comparable groups of adopters and non-adopters based on observable characteristics. Table 5, Table 6, Table 7, Table 8 show the results for the different tilapia aquaculture systems and production practices.

Results show that yields were 2.2 t higher under monoculture than polyculture with mullet (p-value <0.01). The variable cost of production was USD 0.38 lower per kg of tilapia produced under monoculture than polyculture. Consequently, both the gross margins and benefit cost ratio were higher under monoculture than polyculture. Results further reveal that FCR under polyculture was 21% higher than monoculture systems. These results support those of descriptive analysis presented in Section 3.2.

Our results suggests that stocking density affects economic, food security, and environmental outcomes. We found that systems characterized by low stocking density (0.24–2.98 fingerlings m^{-2}) generated 2.9 t ha^{-1} lower tilapia yields and were less profitable compared to those that utilized higher stocking rates. However, FWC was 57% lower in systems with low stocking densities (0.24–2.98 fingerlings m^{-2}) than in systems with higher stocking densities. At stocking densities of 3.02–3.57 fingerlings m^{-2}, we observed a modest increase in tilapia yield by 592 kg ha^{-1}. Similarly, FWC declined by 31.8% and FCR reduced by 12.5%. However, farmers who stocked 3.02–3.57 fingerlings m^{-2} had a 14% reduction in their FCS. At higher stocking density of 3.67–7.14 fingerlings m^{-2} yields increased by 2.1 t ha^{-1}. In addition, FCS increased by 9.8%. However, at such a higher stocking density FWC increased by 37.4%.

In addition to stocking density, our results suggests that the size of fingerlings stocked has implications on economic, social, and environmental performance. We found that farmers who stocked fingerlings of weight <0.25 g obtained 1.7 t ha^{-1} more tilapia yield than their counterparts stocking larger fingerlings. In addition, farmers who stocked fingerlings at weight <0.25 g had their production costs reduced by 53%, more than doubled the gross margins, and had their benefit-cost ratio increased by 37%. However, we also observed trade-offs. We find that the FCS of farmers who stocked fingerlings at weight <0.25 g was 45% lower compared to their counterparts who stocked larger-sized fingerlings. On the one hand, farmers who stocked fingerlings at the weight of 0.3 g–0.5 g obtained 656 kg ha^{-1} less tilapia yield and experienced 33.4% increase in FWC than those who used other stocking weights. On the other hand, farmers who stocked at the weight of 0.3 g–0.5 g had 11% increase in their FCS and a 9.8% reduction in FCR. Aquaculture systems characterized by stocking of large-sized fingerlings (0.75–3.0 g) generated 1.8 t ha^{-1} less tilapia yield, USD 80 cents more cost per kg of tilapia produced, and USD 70 cents less gross margin per kg of tilapia produced than otherwise. In addition, FCR was 19.5% higher among farmers who used large-sized fingerlings (0.75–3.0 g) than otherwise. However, farming households who used large-sized fingerlings (0.75–3.0 g) experienced 15.3% higher FCS and 38.9% lower FWC than those who used alternative sizes of fingerlings.

Our results show that farmers who used pellet feed only and both pellet and extruded feeds had 1.7 t ha^{-1} and 1.3 t ha^{-1} lower yields, respectively, whereas farmers who used extruded feed only had a 1.2 t ha^{-1} higher yield, compared to their counterparts. Farmers who used pellet feed only and both pellet and extruded feed had a substantial reduction in FWC, whereas those who used extruded feed only had an increase in FWC.

Table 5
Impact of species diversification on sustainability outcomes.

Outcome / treatment variable	Treated	Control	ATT	t-statistic
Tilapia yield (t ha^{-1} yr^{-1})	8420	10,612	−2192	−4.64***
Variable cost kg^{-1} of tilapia	1.30	0.92	0.38	4.89***
Gross margins kg^{-1} of tilapia	0.45	0.70	−0.25	−1.87*
Benefit-cost ratio	1.81	2.23	−0.42	−1.68*
Food consumption score	43.93	40.93	3.00	1.00
Fresh water consumption	11.21	14.54	−3.32	−1.16
Feed conversion ratio	1.42	1.17	0.25	4.42

Table 6
Impact of stocking density on sustainability outcomes.

Outcome / treatment variable	Treated	Control	ATT	t-statistic
Panel A: *Stocking density (0.24–2.98* fingerlings m^{-2})				
Tilapia yield	7198.68	10,078.33	-2879.65	−9.02***
Variable cost kg^{-1} of tilapia	1.27	1.08	0.19	1.60
Gross margins kg^{-1} of tilapia	0.45	0.67	−0.22	−1.81*
Benefit-cost ratio	1.79	2.09	−0.30	−2.49***
Food consumption score	43.93	44.38	−0.45	−0.21
Fresh water consumption	7.83	13.67	−5.84	−3.14***
Feed conversion ratio	1.53	1.28	0.25	3.46***
Panel B: *Stocking density (3.02–3.57 fingerlings* m^{-2})				
Tilapia yield	9149.03	8557.07	591.96	1.66*
Variable cost kg^{-1} of tilapia	1.25	1.22	0.03	0.31
Gross margins kg^{-1} of tilapia	0.50	0.49	0.01	0.07
Benefit-cost ratio	1.99	1.81	0.18	1.19
Food consumption score	39.66	45.20	−5.54	−2.58***
Fresh water consumption	9.87	13.01	−3.14	−1.65*
Feed conversion ratio	1.28	1.44	−0.16	−2.98***
Panel C: *Stocking density (3.67–7.14 fingerlings* m^{-2})				
Tilapia yield	10,107.95	8173.85	2064.24	5.86***
Variable cost kg^{-1} of tilapia	1.14	1.24	−0.10	−1.17
Gross margins kg^{-1} of tilapia	0.56	0.49	0.07	0.71
Benefit-cost ratio	1.85	1.87	−0.02	−0.15
Food consumption score	46.26	41.74	4.52	2.01**
Fresh water consumption	16.92	10.59	6.33	2.70***
Feed conversion ratio	1.30	1.37	−0.07	−1.20

4. Discussion

4.1. Benchmarking tilapia aquaculture systems in Egypt

This study provides a benchmark on the status of tilapia aquaculture systems in Egypt, and its sustainability outcomes. Previous studies identified semi-intensive polyculture of tilapia as the most common tilapia culture in Egypt (Macfadyen et al., 2012; Nasr-Allah et al., 2020). Correspondingly, this study found that polyculture in earthen ponds was the dominant aquaculture system; we found that 81.6% of sampled farms cultivated tilapia in polyculture with mullet, while only 18.4% produced tilapia in monoculture (Table 1). This finding aligns with other studies reporting that the prevalence of monoculture tilapia farming within their sample was 13% (El-naggar et al., 2008) and 30% (Nasr-Allah et al., 2020).

We also found that the stocking density in tilapia monoculture was higher than in polyculture (Table 2), which supports the observation of Nasr-Allah et al. (2020) that there are significant differences in stocking practices across aquaculture systems with different levels of diversification in Egypt. High stocking rates in tilapia monoculture has been attributed to the tilapia's tolerance to low levels of dissolved oxygen (DO), a condition that can occur at high stocking densities (Mengistu et al., 2020a; Mengistu et al., 2020b). The reduced stocking density observed in tilapia-mullet polyculture systems serves to improve mullet survival rates, which is less tolerant to low levels of DO than tilapia (Abdel-Gawad and Salama, 2007; Hoang et al., 2018).

Our study also found that fish yields are higher in monoculture than polyculture systems (Table 2), with the observed average yields for monoculture being similar to other studies (10.3 t ha^{-1} yr^{-1}) (Nasr-Allah et al., 2020). Importantly, we found no significant difference in tilapia yield across farm size categories (small-scale, medium-scale and large) (Table 2). This is contrary to a previous study from Egypt that

Table 7
Impact of seed size (weight at stocking) on sustainability outcomes.

Outcome / treatment variable	Treated	Control	ATT	t-statistic
Panel A: *weight at stocking (<0.25 g)*				
Tilapia yield	9993.98	8261.45	1732.53	4.59***
Variable cost kg^{-1} of tilapia	0.86	1.32	−0.46	−4.65***
Gross margins kg^{-1} of tilapia	0.85	0.37	0.48	4.32***
Benefit-cost ratio	2.30	1.68	0.62	4.07***
Food consumption score	30.53	44.25	−13.72	−7.17***
Fresh water consumption	9.49	10.19	−0.70	−0.32
Feed conversion ratio	1.31	1.38	−0.07	−0.96
Panel B: *weight at stocking (0.3 g – 0.5 g)*				
Tilapia yield	8452.36	9108.33	−655.97	−2.17**
Variable cost kg^{-1} of tilapia	1.20	1.28	−0.08	−0.78
Gross margins kg^{-1} of tilapia	0.50	0.48	0.02	0.19
Benefit-cost ratio	1.82	1.94	−0.12	−0.86
Food consumption score	45.38	40.73	4.65	2.22**
Fresh water consumption	13.99	9.31	4.68	2.54***
Feed conversion ratio	1.32	1.45	−0.13	−2.04**
Panel C: *weight at stocking (0.75 g – 3 g)*				
Tilapia yield	7250.84	9027.05	−1776.21	−3.63***
Variable cost kg^{-1} of tilapia	2.10	1.30	0.80	3.14***
Gross margins kg^{-1} of tilapia	−0.35	0.35	−0.70	−2.99***
Benefit-cost ratio	1.14	1.79	−0.65	−3.94***
Food consumption score	48.77	41.29	7.48	2.13*
Fresh water consumption	5.68	7.89	−2.21	−1.65*
Feed conversion ratio	1.74	1.40	0.34	2.52**
Panel D: *weight at stocking (>4 g)*				
Tilapia yield	9278.14	8796.99	481.15	1.02
Variable cost kg^{-1} of tilapia	1.14	1.08	0.06	0.49
Gross margins kg^{-1} of tilapia	0.65	0.65	0.00	0.01
Benefit-cost ratio	2.02	2.03	−0.01	−0.04
Food consumption score	47.65	44.55	3.09	1.24
Fresh water consumption	9.93	9.65	0.28	0.12
Feed conversion ratio	1.49	1.32	0.07	0.78

investigated the economic performance of tilapia monoculture system (but following different aquaculture system categorizations) found a negative relationship between pond size and tilapia yield (Hebicha et al., 2013). The relatively higher yields (though statistically insignificant) observed for small-scale farmers (Table 2), suggest that small-scale farmers can be as productive as their medium-scale and large-scale counterparts, despite the myriad production challenges they experience (Mwanja and Nyandat, 2013; Adeleke et al., 2021; Kaleem and Bio Singou Sabi, 2021).

The result of the cost and return analysis (CRA) indicate that tilapia polyculture systems had a negative statistically significant relations with gross margin estimates compared to monoculture systems (Table 3), as also observed in other studies (Nasr-Allah et al., 2020). Conversely, the significantly lower variable costs in monoculture systems seem to contradict previous results that observed higher variable costs in tilapia monoculture than polyculture system due to higher FCR (Nasr-Allah et al., 2020).

Our results demonstrate that stocking small-sized fingerlings and increasing stocking rate to 3–7 fish m^{-2} was more profitable than stocking large-sized fingerlings at a lower stocking rate (Tables 6-7). These results are consistent both with OLS and the PSM estimates (Table 5, Table 6, Table 7) and are close to Mengistu et al. (2020b) who found that improving farm management to optimize stocking density (3–5 fish m^{-2}) was crucial for enhancing the performance of tilapia aquaculture systems. However, the range for stocking density considered in our study is larger than that reported by Mengistu et al. (2020a, 2020b). Previous studies have shown that pond water quality tends to decrease as stocking density increases (Abdel-Tawwab, 2012); thereby reducing productivity due to poor fish growth and reduced survival rates (Wu et al., 2018; Abdel-Tawwab, 2012; Mengistu et al., 2020a, 2020b). This helps explain our results, where we observe that high stocking density increased FWC in ponds as farmers managed low dissolved oxygen by increasing the frequency of pond water exchange (Table 6).

Table 8
Impact of feeding practices on sustainability outcomes.

Outcome / treatment variable	Treated	Control	ATT	t-statistic
Panel A: *Pellet feed only*				
Tilapia yield	7220.81	8912.33	−1691.52	−2.33***
Variable cost kg^{-1} of tilapia	0.89	1.17	−0.28	−2.04**
Gross margins kg^{-1} of tilapia	0.63	0.60	0.03	0.16
Benefit-cost ratio	1.81	1.87	−0.06	−0.32
Food consumption score	35.25	42.51	−7.26	−1.20
Fresh water consumption	4.26	9.15	−4.89	−2.53***
Feed conversion ratio	1.43	1.47	−0.04	−0.21
Panel B: *Extruded feed only*				
Tilapia yield	9025.54	7797.03	1228.51	3.14***
Variable cost kg^{-1} of tilapia	1.20	1.22	−0.01	−0.06
Gross margins kg^{-1} of tilapia	0.51	0.53	−0.02	−0.13
Benefit-cost ratio	1.87	1.92	−0.05	−0.32
Food consumption score	42.66	45.96	−3.30	−1.30
Fresh water consumption	12.07	7.57	4.50	3.20***
Feed conversion ratio	1.37	1.38	−0.01	−0.08
Panel C: *Pelleted & extruded feed*				
Tilapia yield	7542.90	8857.27	−1314.37	−2.86***
Variable cost kg^{-1} of tilapia	1.50	1.11	0.39	1.64*
Gross margins kg^{-1} of tilapia	0.30	0.58	−0.28	−1.26
Benefit-cost ratio	1.76	1.85	−0.09	−0.66
Food consumption score	49.87	42.34	7.53	2.78***
Fresh water consumption	9.24	13.02	−3.78	−1.86*
Feed conversion ratio	1.55	1.36	0.19	1.34

The weight at stocking reported in previous studies (e.g., (Wu et al., 2018; Abdel-Tawwab, 2012;) was much higher compared to the weight observed in the current study (Table 7). In the current context, farmers increased the stocking density to compensate for the small size of fingerlings and as a strategy to account for mortality. Contrary to Mengistu et al. (2020a, 2020b), we found that farmers stocking large-sized fingerlings experienced lower profitability, at all levels, compared to those stocking small-sized fingerlings (Table 7).

Most previous studies on the performance of tilapia systems have focused on economic outcomes such as productivity and profitability (e.g., Hebicha et al., 2013; Nasr-Allah et al., 2020; Tran et al., 2021). Our study results suggests that, beyond differentiated economic outcomes, differences in the characteristics and practices/activities of tilapia aquaculture systems have broader ramifications for other sustainability outcomes such as food security and environmental performance. In particular, while stocking at the density of 3.6–7.1 fish m^{-2} correlated with the FCS significantly (Table 6) and had higher tilapia yield (Table 6), results in Table 6 (Panel B) seem to suggest that a modest increase in yield will not improve food security. Consequently, it seems that yields alone may not increase food security, as there seem to be much more complex interlinkages. For example, results of panel A in Table 7 show that although stocking very small fingerlings generated significant yield gains, at the same time the FCS decreased. These results contrast panels B and C where we observed that although yield declined with an increase in the stocking weight, the FCS improved.

Collectively, the analysis outlined above provides an important direction to move from mono-dimensional surveys to holistic integrated approaches to assessments and data, to gain an enhanced understanding of the dynamic functioning of aquaculture systems.

4.2. Balancing the synergies and trade-offs of sustainable aquaculture

The integrated analysis conducted in this study shows that there are synergies and trade-offs, both between and within the three sustainability outcome dimensions considered: economic, social, and environmental. In terms of synergies, the study has shown the effect of different stocking densities on yield increase, FWC reduction, and FCR improvement (Table 6 panel B). The study suggests that increased yield and improved food security can be achieved by changing the stocking densities in the farming system (Table 6 panel C). In Table 7, we observe that changes in stocking weight was associated with food security (improvement) and FCR (reduction) (Panel B). Similarly, increased food security negatively correlates with FWC (Table 7, panel C).

In terms of trade-offs, our results show that although FWC is lower at very low stocking densities (0.24–2.98 fingerlings m^{-2}), this is associated with a loss of yield too (Table 6, panel A). At higher stocking densities (3.67–7.14 fingerlings m^{-2}), yield gains were accompanied with an increase in FWC (Table 6, Panel C). For stocking weight, we found that when the weight was between 0.3 and 0.5 g, FCR was lower but yield also declined. Similarly, stocking at the weight of 0.75-3 g was associated with lower FWC and yield. Furthermore, farmers who used pelleted feed either in isolation or in combination with extruded feed had lower FWC and lower yield. Similarly, farmers who used extruded feed in isolation had higher yield but had more FWC. Together, these results suggest a trade-off between objectives of increasing productivity, on one hand, and optimizing environmental gains, on the other hand.

In this study, our results suggest trade-offs within the environmental dimension when achieving reduced FWC comes at the expense of increased FCR and vice versa. For example, at low stocking densities (0.24–2.98 fish m^{-2}), FWC reduced but FCR increased (Table 6). Similarly, stocking at 0.3–0.5 g was associated with reduced FCR and increased FWC while stocking at 0.75-3 g was associated with a reduced FWC and an increase FCR (Table 7).

Trade-offs between and within sustainability outcomes suggest that a more responsible and realistic approach to sustainable aquaculture system (and its intensification) would be to recognize that the achievement of win-win situations is not always straightforward and that difficult socioeconomic political choices must be made to minimize trade-offs (Béné et al., 2019); Liu et al., 2013). The findings further suggest the need to consider multiple outcomes even within a specific dimension of sustainability when assessing impacts of aquaculture systems and practices.

4.3. Policy and practice implications and recommendations

Beyond their academic importance, our findings have important implications for policy and practice. Currently, Egyptian aquaculture is at a crossroads with demand for fish rising, and aquaculture facing various successes and challenges (see Section 1). Both the Egyptian government and the private sector are now facing a complex situation that both increases the difficulty of making policy decisions and investments and creates pre-conditions that the outcomes of these decisions will be manifold for the Egyptian economy, food security and society. In this sense, understanding the performance of tilapia monoculture and polyculture systems is not only relevant to the Egyptian aquaculture industry, but has broader relevance to the Egyptian as society and economy, as it can provide relevant insights into how sustainable aquaculture systems can be designed, developed, and supported.

Considering the above, the findings of this study have important implications for policy- and decision-makers, and investors, including farmers. Developing policies and incentives that support the adoption of better or improved management practices needs to be at the core of improving the sustainability of aquaculture systems in Egypt. Based on the findings of this study, policies should seek to promote best management practices, including feed, fish health and water management since they are key to improving farmers' economic gains and reducing the environmental impact of tilapia farming. Therefore, strategies and investments to support the adoption of better or improved management practices must be viewed as a priority for the sustainable development of the tilapia sector.

As an example, efforts to reduce unit feed costs and improve feed management practices would be crucial to enhance the sustainability of the tilapia sector. Looking at the critical role that feed, and feed management play in determining farm economic viability and food security, and environmental impacts, policies and investment strategies need to support the adoption of better management strategies among tilapia aquaculture farmers. Support could be tailored towards improved feed management practices, including selection of appropriate feed, quantity of feed and feeding methods. Extension advice on the economics and cost-benefit of these practices should be prioritized. Literature suggests that awareness of the costs and benefits of feed management practices in aquaculture will help farmers to develop improved feed management strategy to reduce unit feed costs, increase farm profits and reduce negative environmental impact (Ahmed, 2007; Rola and Hasan, 2007). Similarly, it would be important for aquaculture interventions to focus on supporting production strategies that maximize economic benefits, reduce negative environmental impacts and support food security. In which case, interventions could support the adoption of optimal stocking rates and size at stocking, and optimal species composition in production ponds (monoculture vs polyculture).

Advancing this line of research, to characterize and benchmark aquaculture systems, different actors with vested interests in a sustainable aquaculture sector should seek to improve the evidence base (how it is collected/generated) about the characteristics and performance of aquaculture systems, while complementing existing statistical databases. Arguably, aquaculture policy and investment decisions need to be grounded in more comprehensive and coherent investments to generate fit-for-purpose data and benchmark the aquaculture industry for key aquaculture species and systems, as a means of assessing their performance, progress and enabling policies and investments. In this light, the use of digital technologies and related solutions can be important for boosting the development of comprehensive and dynamic assessment tools to produce benchmarking information and data about systems' performance.

In practice, public sector/policy institutions should collaboratively develop appropriate policies hinged on incentives for the adoption of sustainable aquaculture systems. For the private sector specifically, efforts should be geared towards developing innovative, sustainable production methods that combines socio-economic and environmental sustainability aquaculture systems. This could be done by localizing the technologies for easy adoption by the average farmer such as best management practices in aquaculture. Finally, Civil Society Organizations (CSOs) are expected to provide the watchdog role in the realization of sustainable aquaculture under the framework of the SDGs i.e., Responsible consumption and production (SDG 12), Life below water (SDG 14) and Climate action (SDG 13). This research could assist CSOs in providing the relevant information on which to base their advocacy role. This advocacy role could target policy institutions to develop policies and the private sector to adopt resilient and sustainable aquaculture production methods. The outcomes of these approaches could be enhanced through CSOs strategically positioning themselves as collaborators with private sector and other stakeholders and not adversaries in the achievement of the SDGs.

Although the above implications and recommendations are specific for Egypt, they could have broader applicability in other countries with significant tilapia production sectors, whether in Africa or other developing countries. In any case, regardless of the geographical context of these recommendations, it is recognized that extensive stakeholder discussions would be needed to transform the study recommendations into further policy actions and investments. Indeed, it is not the intention of this study to provide practical solutions that can support the idea of an overly simplistic approach to the sustainability of tilapia aquaculture systems in Egypt and beyond. Therefore, there is need for policy decisions to consider the roles and interests of the various actors concerned in the sustainable development of aquaculture and aquatic food systems more broadly.

5. Conclusion

This study characterized and benchmarked tilapia aquaculture systems and their sustainability performance in Egypt in terms of economic, food security, and environmental outcomes. The study shows that tilapia aquaculture is profitable in both monoculture and polyculture systems, and that, on balance, the former system generates better on-farm economic performance than the latter. A certain level of heterogeneity is observed in the contribution of aquaculture systems and management practices related to different levels of economic, food security, and environmental outcomes.

Such comprehensive information is indispensable for understanding both the current performance and future potential of aquaculture systems. We argue that the lack of data about aquaculture systems has contributed to less-than-optimal policy decisions and practical solutions in the past. The robust assessment of the sustainability performance of aquaculture systems and the factors affecting them is essential for informing effective food security and environmental conservation efforts by governments as well as by other stakeholders, including the private sector. In this sense aquaculture policy and investment decisions need to be grounded in more comprehensive and coherent efforts to generate data and in benchmarking the aquaculture industry for key aquaculture species and systems. The approach outlined in this paper could have broader applicability beyond Egypt, but further research and investments will be required to be applied to other geographies and consolidate this approach.

CRediT author statement

Cristiano M. Rossignoli, Kelvin Mashisia Shikuku, Ahmed M. Nasr-Allah, Arjen Roem, Alaa Badr, Harrison Charo-Karisa, and Nhuong Tran designed the study. Kelvin Mashisia Shikuku, Cristiano M. Rossignoli, Nhuong Tran, Ashraf S. Sbaay, Ahmed M. Nasr-Allah, and Alaa Badr supported the data-gathering process. Cristiano M. Rossignoli, Kelvin Mashisia Shikuku, Ahmed M. Nasr-Allah, Timothy Manyise, Eric Brako Dompreh, and Alexandros Gasparatos analyzed the data and reports from the fieldwork. Cristiano M. Rossignoli, Timothy Manyise, Kelvin Mashisia Shikuku, Ahmed M. Nasr-Allah, Patrik J. G. Henriksson, Eric Brako Dompreh, Rodolfo Dam Lam, Denise Lozano Lazo, Arjen Roem, Roberta Moruzzo, Alexander Tilley, and Alexandros Gasparatos wrote, reviewed, and edited the manuscript. All authors contributed to the article and approved the submitted version.

Author contribution

All the authors contributed equally to this article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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