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Sustainable intensification of genetically improved farmed Tilapia (GIFT) in Timor-Leste's farming systems: Challenges and opportunities

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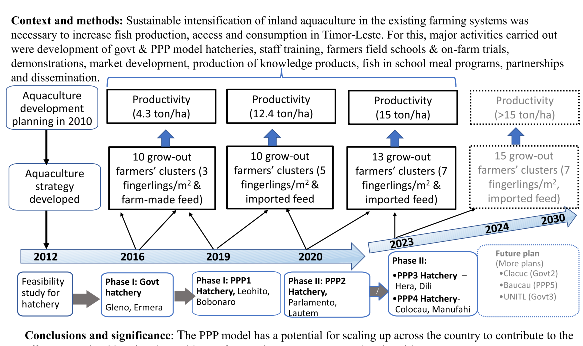
HIGHLIGHTS

- Sustainable intensification of genetically improved farmed tilapia (GIFT) in the subsistence farming systems
- On-farm trialsfollowed unique methods, fostering linkages across value chain for provisioning of input and services
- Fish yield increased to 12.4 t/ha/cycle from 4.3 t/ha/cycle (~300% increment) as a result of sustainable intensification
- One-third (33%) of the tilapia produced by farmers contributed to the food and nutrition security of the rural communities
- Economically, small-scale aquaculture has proven to be highly attractive, with a gross profit of 136%
- The proven aquaculture development model has potential for scaling in Timor-Leste and the pacific island nations

GRAPHICAL ABSTRACT

Holistic approach to sustainable intensification of genetically improved farmed tilapia (GIFT) in Timor-Leste



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ABSTRACT

CONTEXT: There is a growing appreciation of the role of aquaculture in improving food and nutrition security in Timor-Leste. The Timor-Leste government's National Aquaculture Development Strategy (NADS; 2012–30) envisions to increase domestic aquaculture production to 12,000 tons to achieve per capita fish consumption of 15 kg annually by 2030. However, aquaculture development is constrained by limited access to quality seed, feed, and improved technologies. WorldFish has been collaborating with the Ministry of Agriculture and Fisheries since 2015 to help realise the target.

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OBJECTIVE: The objective was to present step-wise interventions – Genetically Improved Farmed Tilapia (GIFT) hatcheries establishment and monosex seed production and distribution; conduct of on-farm grow-out trials; training and capacity building; and extension, communication and marketing services - carried out, and demonstrate how availability, accessibility and consumption of fish could be increased sustainably in the subsistence farming systems of Timor-Leste.

METHODS: Farmers' participatory grow-out trials following better management practices (BMPs) were conducted in two phases from 2015 to 2023 across ten farmers clusters in four municipalities in inlands. The trials in Phase 1 tested GIFT stocked at 3 fingerlings/m^2 using green water in ponds and fed with locally made plant-based feed. In Phase 2, trials tested GIFT stocked at 5 fingerings/m^2 with high quality imported pelleted feed supplemented with local feed and green water. To facilitate scaling, local service providers, feed importers and fish market operators were trained to facilitate input supply and output marketing.

RESULTS AND CONCLUSIONS: In Phase-1, one existing public hatchery was upgraded for producing and supplying quality GIFT broodstock to private hatcheries and one private hatchery was established with public-private partnership (PPP) model. On-farm trials showed that farmers following BMPs and feeding with farm made feed achieved fish yield averaging 4.3 ± 1.5 t/ha/11 months production cycle. In Phase-2, PPP model hatcheries were established; nursery operators connected to each hatchery started nursing fry to fingerlings to local farmers. On-farm trials results managed by 169 farmers in 417 ponds during 2020–2022 showed fish yield of 12.4 ± 0.1 t/ha/ 6 month cycle with full BMPs, suggesting the viability of GIFT intensification across Timor-Leste. Continuous technical backstopping of public and private sectors, however, is crucial for scaling and sustainable intensification of aquaculture.

SIGNIFICANCE: GIFT aquaculture development model of Timor-Leste has potential for scaling across the country for reducing peoples' malnutrition and poverty. The model can also potentially be replicated to other small island nations of the Asia-Pacific region and beyond.

1. Introduction

Among the United Nation's 17 Sustainable Development Goals (SDGs), Goal 2 aims at ending hunger and all forms of malnutrition by 2030 (UN, 2015). There are indications that this goal will be difficult to achieve unless more concerted efforts are made in implementing effective action plans by countries with high incidence of malnutrition and poverty. Timor-Leste is one of them. A small half-island country of 1.3 million people with an annual population growth rate of 2.4% and high level of poverty (42%), Timor-Leste ranks 110th out of 121 countries in the Global Hunger Index (GHI) (Andersen et al., 2013). Food demands are not met, people are chronically food insecure and suffer from malnutrition, as manifested in the high prevalence of children under five that are stunted (58%), underweight (60%), and that are wasting (26%) (Andersen et al., 2013; Concern Worldwide and Welthungerhilfe, 2022). Chronic food insecurity affects >60% of its population during the dry season (May to October) (IPC, 2023). Despite some improvements in food security in recent decades, undernutrition remains too high and continues to be a priority concern in Timor-Leste (Steenbergen et al., 2019; Bonis-Profumo et al., 2022; IPC, 2023). As a young nation with newly established government institutions, rapid population growth, and a history of conflict, the country faces many challenges in improving food and nutrition security and realizing economic growth.

Although agriculture contributed to only 17.1% of the GDP in 2016, similar to other small island nations in the Pacific (GDS, 2017), almost 90% of Timorese' livelihoods depend on subsistence or semi-subsistence agriculture dominated by crop farming and raising livestock. On the other hand, a small proportion (<5%) of households are also engaged in artisanal fisheries and small-scale aquaculture for their livelihoods (GOTL, 2015). A carbohydrate-based diet (comprising for example maize, rice, cassava, taro, sweet potato, beans and vegetables) is the major source of calories while animal source foods (such as chicken, beef, goat meat, and fish) are consumed only occasionally, as these are not only expensive but also not easily available in rural areas. The need for increasing access to animal source foods is considered vital to improving the nutritional status of the resource-poor population. Capture fisheries production in Timor-Leste accounts for only around 5000 metric tons of fish annually, and this available only in coastal areas and sufficient to only partially meet the fish demand of coastal people (World Bank, 2021). Due to lack of post-harvest handling, transportation and storage systems, wild caught fish, if not consumed immediately after catching, spoil within a day and cannot be transported to inland areas. Freshwater aquaculture has been rapidly expanding around the world and, especially in Asia, it has contributed approximately 93% to global fish production with huge potential for rapid increases in fish supply globally (Edwards et al., 2019). Integrating fish farming into the existing crop-livestock based subsistence farming systems in inland Timor-Leste could be a viable option for diversifying rural livelihoods and contributing towards meeting food and nutrition demands of the country.

The strategic development plan (SDP) of Timor-Leste (2011−2030) emphasizes the development of sustainable fisheries and aquaculture for the reduction of poverty and increasing food and nutrition security and economic growth of the nation (SDP, 2011). The National Directorate of Fisheries and Aquaculture (NDFA), now renamed the National Directorate of Aquaculture (NDA), under the Ministry of Agriculture and Fisheries (MAF), now renamed as the Ministry of Agriculture, Livestock, Fisheries and Forestry (MALFF), has also emphasized the need for the development of aquaculture based on low-cost technologies that are environmentally benign, socially acceptable, and economically viable (NDFA-MAF, 2012b). Analysis of the aquaculture situation during 2011–12 (NDFA-MAF, 2012a) revealed that the expansion and intensification of freshwater aquaculture in inlands was largely constrained by the unavailability of production inputs and viable technologies, and inadequate human resources within the NDA (former NDFA), despite its high potential across the country. Development of sustainable aquaculture technologies, adequate human resources, input supply systems, provision of markets, infrastructure, and a conducive policy environment were considered vital for harnessing aquaculture development potential in the country (Pant et al., 2011).

In its National Aquaculture Development Strategy (NADS) prepared in 2012, the government aimed to increase national per capita fish consumption from 6.1 kg in 2012 to 15 kg by 2030 which will require a total of 30,000 tons of fish supply annually by 2030. The strategy envisions that aquaculture (including marine, coastal and inland) should contribute approximately 40% of total fish supply while the remainder 60% is expected to come from capture fisheries and imports (NDFA-MAF, 2012b). It was a challenge considering the then very limited total fish pond area (approx. 40 ha), single fish cropping cycle/yr, low fish productivity (approx. 1 t/ha/yr), low technical and managerial capacity of researchers and government staff, and the very few fish farmers, all with low skills and knowledge of aquaculture (NDFA-MAF, 2012a; Pant et al., 2011). Moreover, it was also realized that such an ambitious target must be achieved sustainably with stable production and profits and without harming the environment.

Hence, there is a need to diversify and intensify Timor-Leste's agriculture by integrating aquaculture with existing crop-livestock based farming systems and scale-up fish production and supply sustainably by increasing the number of ponds, pond area, and fish production across the country. The most effective approach to sustainably meet the increasing demand for fish would be to promote the sustainable intensification of aquaculture (SIA) by increasing the productivity and efficiency of resource inputs and reducing the negative environmental and social impacts through improved governance, management practices, and adoption of innovative technologies (FAO, 2016). The realization of SIA practices at scale in Timor-Leste, however, was largely constrained by the lack of access to inputs (seed, feed) and services (marketing, extension), as well as institutional support at national and local levels from national and international organizations (Pant et al., 2011; NDFA-MAF, 2012a; López-Angarita et al., 2019).

In response to the above challenges and recognizing the need to increase food and nutrition security, WorldFish, headquartered in Penang, Malaysia, started working in Timor-Leste in partnership with the MALFF (former MAF), I/NGOs and development agencies, and national and local private sector from around 2010. WorldFish introduced Genetically Improved Farmed Tilapia (GIFT), an improved strain of Nile tilapia (*Oreochromis niloticus*) broodfish, in 2015. Since then, (MALFF (former MAF) and WorldFish have been jointly implementing the New Zealand government supported "Partnership for Aquaculture Development in Timor-Leste (PADTL)" Project (Phase 1 and Phase 2) focusing on increased availability, accessibility and consumption of fish (Pant et al., 2019a, 2019b, 2020a). As a key component, the project involved farmer-participatory on-farm grow-out trials and developing better management practices guidelines for GIFT through testing and validation of low-cost technologies. Provision of inputs and services at local level is vital in small-scale aquaculture production systems, as it is not viable for small scale farmers to travel distant locations for procuring input and marketing of fish (Arthur et al., 2022). Hence, PADTL's approach to SIA in Timor-Leste has been to: (i) develop farmer clusters and groups in the potential agro-ecologies (through GIS analysis); (ii) establish a network of hatcheries and nurseries to ensure availability of quality seed at the local level; (iii) support feed importers in making high quality feed available at a reasonable price; (iv) facilitate the establishment of fish markets in populous areas (e.g. Dili); and (v) develop a network of local service providers to facilitate input supply and output marketing effectively.

Over the years, project partners have generated various data through on-farm trials and useful lessons have been learnt that can be shared with the global aquaculture communities and is particularly relevant to the small island nations of the Asia-Pacific region. The objectives of this paper are to:

- present the various interventions carried out by the project to demonstrate how fish production and productivity, and their accessibility and consumption could be increased sustainably; and
- share lessons learnt in the process of sustainable intensification of GIFT culture in the existing farming systems in inland freshwater areas of Timor-Leste and highlight challenges and opportunities for achieving the country's NADS target through SIA.

2. Status of aquaculture in Timor-Leste and project interventions

During the Indonesian regime (1975–1999), freshwater aquaculture in inland areas and saltwater aquaculture with shrimp and milkfish in coastal areas was initiated with the establishment of hatcheries. The operation of hatcheries, however, was discontinued during the conflict period (1999–2001). After the country became fully independent in 2002, aquaculture in both coastal areas and inland got some attention. A government report showed about 280 households being engaged in freshwater aquaculture in 2004, which increased to 1280 households in 2009 but producing only about 46 tons of fish from 41 ha of water area (NDFA-MAF, 2012a). A background analyses in 2011–2012 also showed that freshwater aquaculture was practiced as a part-time farming activity in all municipalities. There were four government hatcheries producing a total of 50,000 fingerlings annually – which was barely sufficient for stocking of 2 ha of pond area (Pant et al., 2011). Assuming a stocking density of 3 fingerlings per m^2, over 1.2 million fingerlings would be required to stock 41 ha of ponds (NDFA-MAF, 2012a).

Freshwater aquaculture is best suited to areas with a favorable resource-base such as availability of water, feed and seed and accessibility, and social and economic context for fish farming. In 2012, a GIS study aimed to assess and map the overall suitability of freshwater aquaculture in Timor-Leste, revealed that the most potential areas were concentrated in Ermera, Baucau, and Bobonaro (NDFA-MAF, 2012a). This study specifically focused on common carp and tilapia, two major fish species commonly farmed in low input – output systems (pond size from 40 to 600 m^2), with 0.5–1.7 t/ha average yield over a 1 year grow out period (NDFA-MAF, 2012a). In 2023, the GIS suitability mapping for freshwater aquaculture was updated with better data resolution (Fig. 1).

The PADTL project, implemented since 2015, follows a holistic approach to increasing availability, accessibility and consumption of fish. Major activities and interventions by the project were conducted in two phases as described below.

2.1. Phase 1 (2015–19) interventions

Considering the high-quality seed as the most important input for the aquaculture development, WorldFish introduced four cohorts of GIFT broodstock from its Headquarters in Malaysia to the government owned hatchery in Gleno, Ermera in 2015 and assisted in upgrading the hatchery's existing facilities for maintaining the genetic quality of broodstock. Since then, the hatchery has been maintaining the genetic quality of GIFT broodfish following rotational breeding of cohorts and supplying high quality broodfish to other public and private hatcheries. In 2019, the first private hatchery was established in Leohitu in Bobonaro municipality with the PPP scheme, a unique model promoted by the PADTL (Pant et al., 2020b). In this scheme, a private hatchery acquires quality broodfish and with technical assistance from the government hatchery, multiplies and disseminates high quality GIFT monosex seed to farmers.

During Phase 1, participating farmers stocked GIFT monosex seed with only 3.5 fingerlings/m^2 in farm ponds, fertilized ponds with organic manure to make green water to enhance in situ production of natural food, and fed fish with the farm made feed using locally available ingredients (e.g., Leucaena leaf meal, maize) consisting of only 18% crude protein (CP). However, feeding GIFT with low CP feed resulted in high feed conversion ratios, slow growth, and long-grow out periods (>11 months) and an average extrapolated fish productivity of 4.3 t/ha (Pant et al., 2019c, 2023b). However, an average productivity of the top 10% of high performers indicated a yield potential of 7.3 t/ha. Based on these findings, a set of guidelines for better management practice (BMP) was developed to increase productivity and viability of small-scale production systems, using a combination of farm made feed and fertilization to increase in situ natural pond productivity (Pant et al., 2019c, 2023b).

2.2. Phase 2 (2020−23) interventions

Phase 2 interventions focused more holistically on increasing availability (i.e., through increased production), accessibility (i.e., through establishing effective marketing and services) and consumption (i.e., though increasing awareness about the nutritional benefits) of fish. The main interventions included increased stocking density from 3 to 5 fingerlings/m^2, making high quality feed accessible to farmers, and

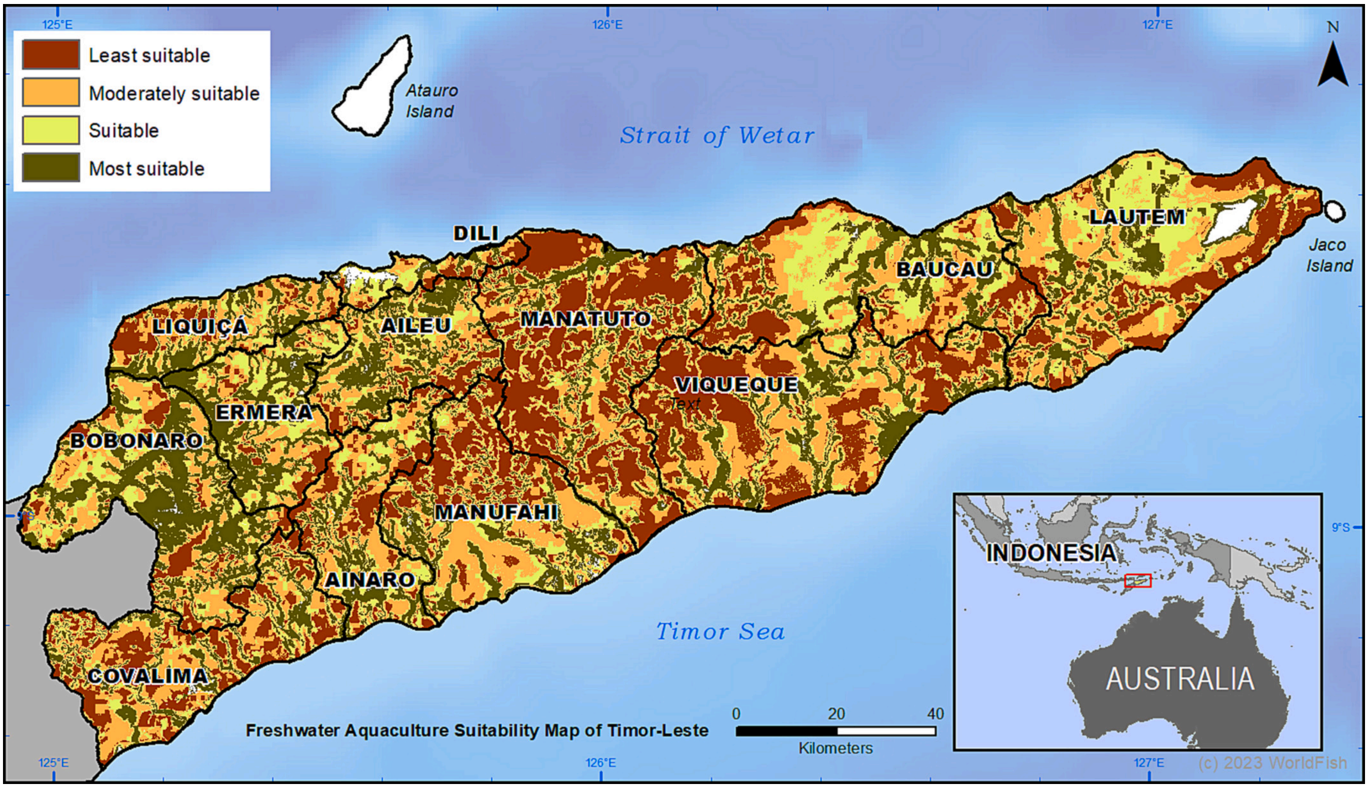

Fig. 1. The refined suitability map for freshwater aquaculture potential in Timor-Leste prepared in 2023.

facilitating input supply and output marketing through Local Service Providers (LSPs), feed importers and fish market operators.

A business model was conceptualised showing the role of private sector in facilitating increased seed production, increased feed availability, and liaising with markets for fish sale (Fig. 2). Under this model, seed production and supply at the local level was ensured by establishing three additional private GIFT hatcheries (Parlamento in Los Palos municipality, Hera in Dili municipality, and Colocau in Manufahi municipality), all based on the PPP model. Two to four GIFT nurseries (that acquire sex reversed fry from private hatcheries and nurse them for 4–6 weeks and sell to local farmers) were connected to each of the hatcheries to ensure easy access to seed by fish farmers; import of good quality pelleted feed, i.e., Hi-Pro-Vite (>30% crude protein, produced by CP Prima, Indonesia) was made available to farmers. The LSPs with their network have been assuring supply of inputs (seed, feed etc.) to local farmers and facilitating fish marketing. The locations of hatcheries, nurseries, farmer clusters, and grow-out farmers in PADTL Phase 1 and Phase 2 are shown in Fig. 3.

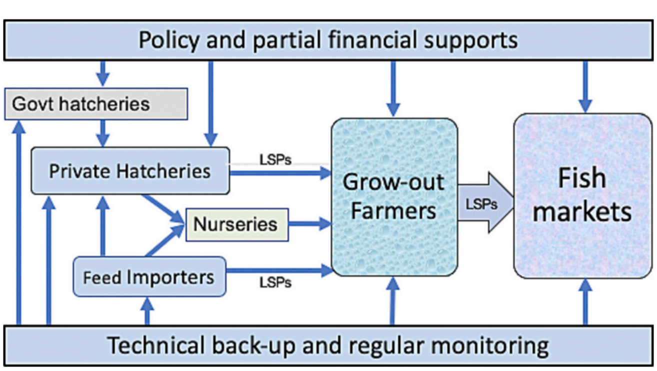

Fig. 2. A business model showing role of public and private sector in scaling.

3. Methodological approaches

Interventions aiming for sustainable intensification of GIFT farming in the existing subsistence farming systems in inland areas included: i) monosex seed production on a mass scale by establishing public and private hatcheries with the PPP model, ii) on-farm trialing of GIFT seed with use of commercially floating feed pellets and adopting other BMPs in ten clusters of four municipalities (Baucau, Bobonaro, Ermera and Lautem) through farmer participatory on-farm trials, and iii) development of private sector networks for effectively supplying input (seed, feed) and services (marketing, extension), and for scaling. Feed production and management using locally available feed ingredients were tried earlier (Pant et al., 2023a). More recently, imported high-quality floating feed pellets have been made available as the main input for nutrients in addition to the in situ production of natural food (phytoplankton) by fertilizing ponds to make water green (Pant et al., 2023b). Likewise, monosex seed production and dissemination by hatcheries using the PPP model is discussed in detail in a BMP (Pant et al., 2020b). This paper focuses on the results of on-farm grow-out trials and approaches used for scaling and SIA with GIFT.

3.1. On-farm trials

On-farm trials were conducted in 2021 and 2022 (PADTL Phase 2) using 417 ponds belonging to 169 farmers (both male and female) groups into 10 clusters located in four municipalities. The clusters in Baucau included Gariuai, Ossoguigui and Goa 7, while in Bobonaro they were Leohitu, Balibo and Batugade, and in Ermera were Faturquero, Poetete and Laubono. In Lautem, only Parlamento was selected. The municipalities and clusters were selected based on various considerations producing a GIS map for aquaculture suitability considering biophysical (water availability, slope, soil pH and soil texture) and social and economic factors (accessibility, market, and input supply including seed and agri-by-products for feed) (NDFA-MAF, 2012a), and in

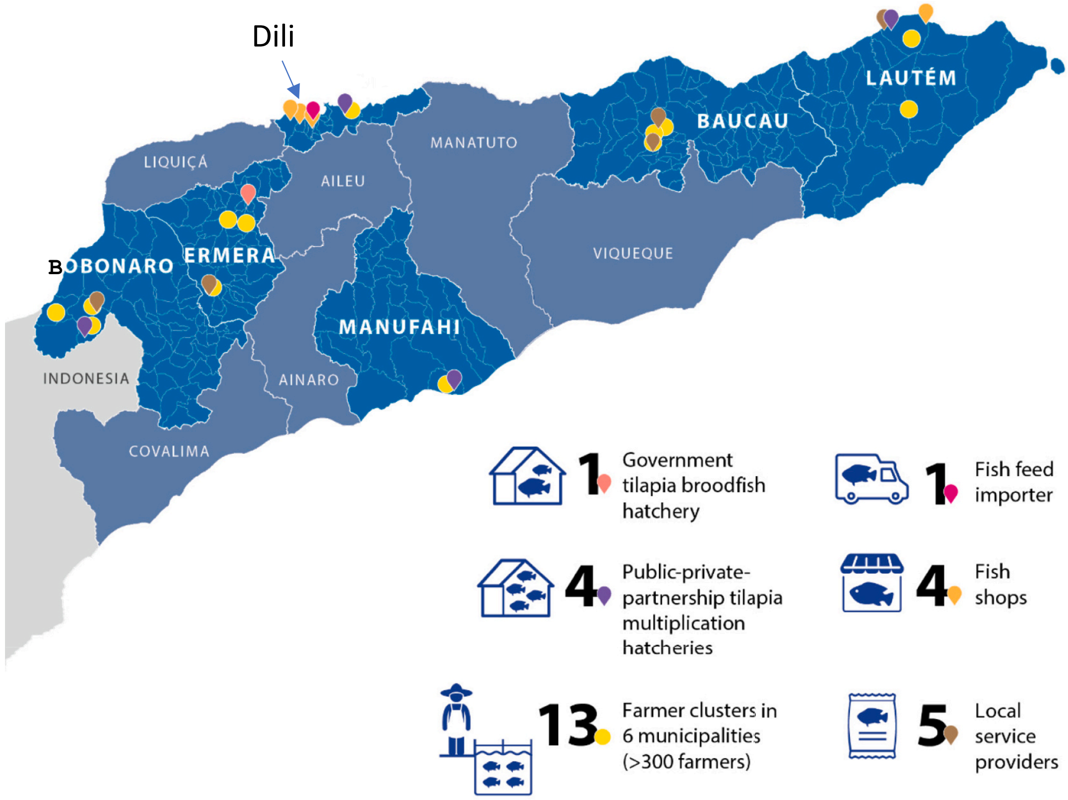

Fig. 3. Locations of hatcheries, nurseries, LSPs, fish markets fed importers, and grow-out farmers clusters in PADTL Phase 1 and Phase 2.

consultations with field based MALFF (former MAF) and project staff and local farmers.

Farmers participating in on-farm trials in each municipality were organized in clusters comprising male and female farmers with the average number of farmers ranging from 6 to 28 per cluster. Each cluster had a leader based in Farmers Field Schools (FFS), responsible for providing modular trainings following a participatory approach developed by FAO. The FFS members meet monthly to share experiences, discuss problems and possible solutions, and plan future activities (De et al., 2013). Farmers participating in on-farm trials were provided with a set of guidelines, through FFS sessions conducted by the project staff and trained local technicians. The guidelines covered pond preparation, fry/fingerling stocking, monitoring fish growth and adjusting feeding rate based on total fish biomass on a monthly basis, pond water quality management, harvesting and marketing. To avoid over feeding or underfeeding, a feeding schedule was developed and fish fed based on their growth with adjustment made according to fish biomass estimated by monthly sampling.

3.1.1. Data collection

In each cluster, the following data were recorded by field technicians and farmers with timely guidance by researchers:

i. Number of households participating in on-farm trials by cluster and municipality;
ii. Number, area and size of ponds;
iii. Number and weight of fish stocked, dead, harvested, consumed, and sold by each household from each pond.
iv. Sampling three times, 5–10 fish per sample/pond to monitor fish growth at 30-day intervals (i.e., Day 0, 30, 60, 90, 120, 150, 180);
v. Average daily weight gain (g/fish/d), estimated as weight gain per fish divided by 30;
vi. Total stocking period (months or days)
vii. Fish productivity (t/ha/cycle);
viii. Amount of feed given weekly to each pond - recorded by farmers;
ix. Gross profit = Total value of fish sale - total variable costs (i.e., costs of seed, feed, fertilizers and labour).

Labour cost was estimated based on the cumulative time spent recorded daily by each farmer and multiplied by daily wages (US$5/d). Feed price varied from US$1.4–1.5/kg, seed from US$0.03 to 0.05/fry depending on size and selling price of food fish from US$3.5–5.0/kg.

3.1.2. Monosex seed production and supply

GIFT monosex seed for the on-farm trials was obtained from the public hatchery in Gleno, Ermera and the earlier established two private hatcheries in Leohitu and Parlamento (and not from the recently established two private hatcheries in Hera and Manufahi). Seed was also sourced from nurseries connected to those hatcheries. The Gleno hatchery has produced and supplied approximately 1.8 million monosex fry to 2959 farmers during 2016–2021, the Leohitu hatchery has supplied nearly 1 million fry to 829 farmers during 2019–2022, and the Parlamento hatchery nearly 0.5 million fry to 287 farmers during 2022. For the on-farm trials for SIA conducted from late 2021 to mid-2022, 231,774 monosex fingerlings were distributed to participating farmers with the average number (±SD) of 23,177 ± 12,693 per cluster. It is worth noting that although farmers were advised to use only monosex GIFT in the on-farm trials, very few farmers in some locations unintentionally used some mixed-sex GIFT fingerlings or other fish species.

3.1.3. Feeds and feeding management

In phase-1, home-made feed was produced using various combinations of locally available ingredients selected after conducting an extensive survey; namely, corn meal, rice bran, taro leaf meal, Leucaena leaf meal, cassava powder, and common salt. However, they were in short supply and farmers felt quite cumbersome in collecting and processing them before making feed. More importantly, its protein content was only about 18%; much less compared to the manufactured feeds (Pant et al., 2023a). Hence, from 2021, high quality floating fish feed pellets in four sizes (1 to 4 mm) manufactured by CP Prima in Indonesia was imported by local private feed suppliers. Although the feed suppliers imported feed containing 20 to 34% protein, all trial participants were advised to use Hi-Pro-Vite feed (31% CP) from a selected supplier. Small pellets (1–2 mm) were used for nursing and for the initial stage of grow-out (first 2 months) and larger pellets (2–4 mm) used for the latter stages. Feeding rate for the grow-out started from 3.5% of biomass with monthly decrease by 0.5% to 1.5% of biomass until harvest. Farmers were provided with feed until the 4th month, and then asked to start selling the larger fish to finance the purchase of commercial feed as well as providing additional family income.

3.1.4. Water quality parameters

Farmers were trained to record water quality parameters (temperature, pH, Secchi disc visibility and greenness of water). Measurements were taken weekly and recorded in pond record books maintained separately for each pond. Pond depth (deepest and shallowest) was measured using a wooden stick with colored marks as gauge inserting into the water column. Pond water colour was observed visually and recorded as: 1 clear; 2 light green; 3 green; 4 dark green; and 5 not green but turbid mainly due to suspended soil particles). Temperature was recorded using a simple thermometer, pH using a standard test-kit based on the colour strips, and water turbidity using a locally made Secchi disc.

3.1.5. Statistical analysis

The agroecological, social and economic contexts, accessibility and level of infrastructure varied across municipalities. Clusters were formed with fish farmers groups within each municipality. Therefore, municipality and cluster were considered as first and second factors respectively for multi-factor ANOVA. Multiple comparisons among the municipalities or clusters were based on the results of Tukey's HSD test and were considered either significant ($\leq$0.05) or highly significant ($\leq$0.01). Differences on production performances were analyzed using One-Way AOVA in SPSS for each variable separately (univariate analysis) across municipalities and clusters considering as factors such as location, landscape, culture, household characteristics, pond type and depth, land ownership/tenure, household head's gender, whether integrated agriculture-aquaculture (IAA) was practiced or not, water quality, and feeding rates.

Multiple regression was conducted to explore relationships between the predictors and the final size of fish sampled on the 120th day. A total of 15 predictors were considered to be important to have effects on the growth of tilapia stocked in ponds during the fully fed culture period of 120 days. These predictors were: household member size; age and education of household head; length, area, width and depth of pond; colour, pH and temperature of pond water; daily feeding rate during the 1st, 2nd, 3rd and 4th month; and Secchi disk visibility. The following regression equation was developed to describe the relationships between significant predictors and their contribution to determining the final size of fish at 120th day.

$$Y = a + b_1X_1 + b_2X_2 + \ldots\ldots\ldots\ldots\ldots\ldots + b_nX_n$$

Where:

Y – Output, i.e., final weight of the fish on the 120th day

a – Constant or intercept

$b_1, b_2, \ldots. b_n$ are the coefficients of significant predictors

$X_1, X_2, X_3 \ldots\ldots\ldots X_n$ are the significant predictors determining the final fish size

3.2. Scaling of aquaculture

For scaling of aquaculture, the main activities included: 1) training and capacity building activities for hatchery staff, feed importers, FFSs and grow-out farmers, nursery operators, and LSPs, 2) extension, communication and dissemination activities, and 3) establishment of live fish markets. Field facilitators (FFs) assigned to each cluster under each municipality assisted farmers in maintaining the data in Pond Records Book and in entering them into a database in Excel, and in compiling and helping prepare reports. To ensure sustainability of the project activities after the project ends, LSPs were organized and trained to strengthen linkages between farmers and input suppliers (hatcheries and feed importers) and ensure ongoing farmer access to seed, feed and other inputs.

4. Results and discussion

4.1. On-farm trials results

4.1.1. Participating households, number and size of ponds, and fish stocked

The number of households participating in the trials; number, area and size of the fish ponds, and number of fish stocked by the participating households varied significantly across municipalities and clusters. A total 169households participated in the trial(ranging from 16 in Lautem to 90 in Bobonaro), comprising a total of 417 ponds (ranging from 43 in Lautem to 165 in Bobonaro). The total pond area was 4.485 ha, ranging from 0.53 ha in Lautem to 1.23 ha in Baucau, while the total number of fish stocked was 231,774, averaging from 15,570 (Ermera) to 29,825 (Bobonaro). The pond size was significantly bigger in Baucau (128 m^2) and Lautem (122 m^2) than in Ermera (80 m^2) (P = $\leq$0.01) and without significant difference between Lautem and Bobonaro. Across clusters, ponds were significantly bigger in Gariuai (164 m^2) than Faturquero or Poetete (53 and 58 m^2, respectively) while fish stocking was lowest in Poetete (4929) and highest in Leohitu (42,693) (Table 1).

4.1.2. Fish growth rate and fish weight

Periodic sampling and measurements of fish (30-day intervals) showed significant differences in fish weight between municipalities or clusters at each sampling date. There was increasing growth trend of tilapia from 120 to 180 days even some of the clusters stopped feeding pellets. Across municipalities, fish weight at day 0 (stocking day) ranged from 1.2 g (Bobonaro) to 1.7 g (Lautem), and across clusters from 0.9 g (Gariuai) to 1.7 g (Parlamento). On the other hand, at day 180, there were no significant differences in fish weight in Lautem, Baucau and Ermera (range: 266–277 g) but was significantly greater than Bobonaro (239 g) (P = $\leq$0.01). Likewise, at day 180, there were no differences in fish weight between clusters in Baucau, while the Faturquero cluster of Ermera had significantly greater fish weight (287 g) than the other two clusters (260 g) and the Balibo cluster of Bobonaro had significantly greater fish weight (268 g) than the other two clusters (225 g). The change in fish weight between any two consecutive sampling dates showed the fastest growth during the first 120 days (0.9–1.9 g/d) and slowest during 150–180 days (0.8–1.8 g/d). Across municipalities, the average growth rate during 0 to 180 days was significantly lower in Bobonaro (1.3 g/d) than the other three municipalities (1.5 g/d) (Table 2). The slow growth rate has resulted in low fish weights in Bobonaro.

Since feed was subsidized until 120 days and feeding was done based on total biomass, participating farmers fed fish regularly until 120 days. Feeding after 120 days however varied among the municipalities or clusters since some farmers continued purchasing feed while other opted to rely solely on natural food produced in situ in the green water. Greenness of water also varied across ponds and no pattern of relation between clusters and green water was detected. Feed used in all clusters was greatest (19–71.8 g/pond/d) during 90–120 days. In Baucau, more feed was used during 120–150 days (37.2–46.3 g/d) compared to 90–120 days (26.8–45.6 g/d), where farmers continued to feed fish until 180 days, presumably due to less green water available in fish ponds. On the contrary, in Ermera, most farmers completely stopped feeding after 120th day, presumably due to financial constraints but fish continued to

Table 1
Total number of households and ponds, total pond area and pond size, and fish stocked and harvested in field trials across municipalities and clusters in Timor-Leste (2020–2022).

Municipality	Cluster No.	Cluster name	Total no. of households	Total no. of ponds	Total area of pond (m^2)	Average size of ponds (m^2)	Total no. of fish stocked
Lautem	1	Parlamento	16	43	5259	122$^{xy\ bc}$	27,264
Baucau	2	Gariuai	6	29	4750	164^{d}	25,112
	3	Ossoguigui	9	23	2130	109^{bc}	9888
	4	Goa7	15	57	6322	111^{bc}	33,324
	Average		**10**	**36**	**4401**	**128^{y}**	**22,775**
	Std.		±4	±15	±1729	±25	±9709
Ermera	5	Faturquero	9	34	1807	53^{a}	9560
	6	Laubuno	20	49	6334	129^{cd}	32,222
	7	Poetete	±4	±16	±933	±58^{a}	±4929
	Average		**11**	**33**	**3025**	**80^{x}**	**15,570**
	Std.		±7	±13	±2367	±35	±11,925
Bobonaro	8	Leohitu	39	71	8264	116^{bc}	42,693
	9	Balibo	24	38	2758	73^{ab}	14,204
	10	Batugade	27	57	6289	110^{bc}	32,576
	Average		**30**	**55**	**5770**	**100^{xy}**	**29,825**
	Std.		±6	±14	±2278	±19	±11,792
Grand total			169	417	44,846	–	231,774
Overall average			**17**	**42**	**4485**	**105**	**23,177**
Std.			±11	±17	±2434	±34	±12,693

Notes: Mean values with different superscripts are significantly different at 0.05. Superscript a, b, c compared among the clusters and x, y, z among the municipalities.

Table 2
Weight of fish (g) monitored at 30-d interval, daily weight gain, and amount feed given to fish per day in field trials across municipalities and clusters in Timor-Leste (2020–2022).

Municipal	Cluster no.	Cluster name	Fish weight (g)				Daily weight gain (g/fish/day)			Amount of pellet fed (g/day/pond)		
	Days g →		0 d	120 d	150 d	180 d	0–120 d	0–150 d	0–180 d	90–120 d	120–150 d	150–180 d
Lautem	1	Parlamento	1.7^{xa}	198$^{y\ bc}$	229$^{y\ de}$	277$^{x\ ab}$	1.64^{yb}	1.51^{ybcd}	1.53^{xbc}	39.6^{xy}	25.2^{yb}	19.0^{yb}
Baucau	2	Gariuai	0.9^{e}	222^{a}	276^{a}	263^{ab}	1.85^{a}	1.83^{a}	1.46^{ab}	45.6^{b}	46.3^{a}	17.7^{b}
	3	Ossoguigui	1.2^{d}	207^{b}	249^{bc}	263^{ab}	1.71^{ab}	1.65^{bc}	1.45^{bc}	26.8^{bc}	46.1^{a}	36.1^{a}
	4	Goa7	1.2^{d}	209^{b}	254^{b}	273^{ab}	1.73^{ab}	1.69^{ab}	1.51^{bc}	34.8^{bc}	37.2^{a}	35.9^{a}
	Average		1.1^{z}	213^{x}	260^{x}	266^{x}	1.76^{x}	1.72^{x}	1.47^{xy}	35.7^{y}	43.2^{x}	29.9^{x}
	Std.		±0.2	±8.6	±14.2	±5.6	±0.07	±0.10	±0.03	±9.4	±5.2	±10.6
Ermera	5	Faturquero	1.3^{c}	196^{bc}	237^{bcd}	287^{a}	1.62^{b}	1.57^{bcd}	1.58^{ab}	30.3^{bc}	0.0^{c}	0.0^{c}
	6	Laubuno	1.2^{d}	203^{bc}	232^{cde}	260^{ab}	1.68^{ab}	1.54^{bcd}	1.44^{c}	71.8^{a}	0.0^{c}	0.0^{c}
	7	Poetete	1.6^{b}	190^{c}	222de	261^{ab}	1.57^{b}	1.47^{cde}	1.44^{bc}	33.4^{bc}	0.0^{c}	0.0^{c}
	Average		1.4^{y}	196^{y}	231^{y}	269^{x}	1.62^{y}	1.53^{y}	1.49^{y}	45.1^{x}	0.0^{c}	0.0^{z}
	Std.		±0.2	±6	±8	±15	±0.05	±0.05	±0.08	±23.1	±0.0^{z}	±0.0
Bobonaro	8	Leohitu	1.2^{d}	159^{d}	213^{ef}	222^{c}	1.31^{c}	1.41^{de}	1.23^{d}	19.0^{c}	4.9^{c}	0.1^{c}
	9	Balibo	1.2^{d}	109^{e}	219de	268^{ab}	0.90^{d}	1.46^{de}	1.48^{bc}	34.0^{bc}	2.1^{c}	0.0^{c}
	10	Batugade	1.2^{d}	115^{e}	196^{f}	228^{c}	0.95^{d}	1.30^{e}	1.26^{d}	40.2^{bc}	9.0^{c}	0.7^{c}
	Average		1.2^{z}	127^{z}	210^{z}	239^{y}	1.05^{z}	1.39^{z}	1.32^{z}	31.1^{y}	5.3^{z}	0.3^{z}
	Std.		±0.0	±27	±12	±24.8	±0.23	±0.08	±0.14	±10.9	±3.5	±0.4
Overall average			1.3	181	233	260	1.50	1.54	1.44	1.54	17.1	10.9
Std.			±0.2	±40	±23	±20.2	±0.33	±0.15	±0.11	±0.15	±19.7	±15.2

Notes: Mean values with different superscripts are significantly different at 0.05. Superscript a, b, c etc. compare among the clusters and x, y, z among the municipalities.

grow bigger because more green water available in fish ponds. In Bobonaro, fish were continued to be fed with small amount to supplement the natural food available through green water (Table 2).

4.1.3. Fish survival, yield and economic analysis

Overall fish mortality was 0.44 ± 0.36% with the highest of 1.81% in Goa7, meaning that the lowest survival was above 98%. This indicates that water quality and overall management was good which in turn resulted in average fish yield to 12.4 ± 0.1 t/ha/180-day cycle across municipalities and clusters. Across municipalities, Lautem and Baucau had about 26% higher fish productivity than Ermera and about 34% higher than Bobonaro. Across clusters, the average fish yield ranged from 10.3 to 15.5 t/ha, with highest in Gariuai (15.5 ± 5.3 t/ha) and lowest in Batugade (10.3 ± 1.5 t/ha) (Table 3**).**

Gross profit analysis was conducted by estimating and comparing the variable costs and revenues from fish farming across municipalities and clusters (Table 3). Major inputs were fish seed, feed and labour wages. Across municipalities, the total extrapolated cost of production (per ha) was lowest for Ermera (US$45,510 ± 4271) and highest for Baucau (US $59,845 ± 10,029), while across clusters, it was lowest for Laubuno (US $41,302) and highest for Goa (US$71,335). Average feed, seed and labour costs were about 79% (range 66.6–81.9%), 12% (10.4–17.2%) and 9% (6.3–16.1% of the total cost respectively. Labour cost was highest in Parlamento (Lautem) compared to the other clusters and three municipalities (Table 3). The gross profit in absolute value (USD/ha) and gross profit percentage (%) also differed considerably across municipalities and clusters. Across municipalities, gross profit was highest in Baucau (US$37,698) and lowest in Ermera (US$22,548) while across clusters, it was highest in Goa (US$47,621) lowest in Laubuno (US$19,429). Gross profit (%) ranged from 98% (Ermera) to 169% (Baucau), with significant differences between these municipalities. However, there were no significant differences in gross profit between Lautem and Ermera and between Baucau and Bobonaro. Overall, the average total cost was US $21,937 ± 1142, gross profit US$29,005 ± 3236, and percentage gross

Table 3
Fish productivity, variable costs, gross revenue and gross profit and gross profit (%) calculated from the field trials across municipalities and clusters in Timor-Leste (2020–2022).

Municipal	Cluster no.	Cluster name	Fish productivity	Variable costs (USD/ha)				Gross revenue and gross profit (USD/ha)		
			(t/ha/180-day cycle)	Seed	Feed	Labour	Total	Gross revenue	Gross profit	Gross profit (%)
Lautem	1	Parlamento	14.6^{xab}	2500	17,986	3457	23,944	50,113	26,169	109%
Baucau	2	Gariuai	15.5^{a}	2500	16,695	1321	20,516	52,848	32,332	158%
	3	Ossoguigui	13.2^{bcd}	2500	18,149	1562	22,211	55,352	33,141	149%
	4	Goa7	13.9^{abc}	2500	19,417	1797	23,714	71,335	47,621	201%
	Average		14.2^{x}	2500	18,087	1560	22,147	59,845	37,698	169%
	SE		±0.3	±00.0	±1362	±238	±1600	±10,029	±8603	±28%
Ermera	5	Faturquero	11.5^{de}	2500	18,439	2689	23,628	45,386	21,758	93%
	6	Laubuno	10.7^{e}	2500	17,903	1471	21,874	41,302	19,429	89%
	7	Poetete	12.1^{cde}	2500	18,502	2383	23,385	49,842	26,457	113%
	Average		11.4^{y}	2500	18,281	2181	22,962	45,510	22,548	98%
	SE		±0.3	±00.0	±329	±634	±950	±4271	±3582	±13%
Bobonaro	8	Leohitu	11.3^{de}	2500	9666	2339	14,505	46,053	31,548	218%
	9	Balibo	10.6^{e}	2500	17,771	1878	22,149	49,190	27,041	122%
	10	Batugade	10.3^{e}	2500	15,708	1218	19,426	49,655	30,229	158%
	Average		10.7^{y}	2500	14,382	1812	18,693	48,299	29,606	166%
	SE		±0.2	±00.0	±4212	±563	±3875	±1959	±2341	±48%
Total			–	25,000	170,237	20,115	215,352	511,076	295,724	–
Overall average			12.4	2500	17,184	2253	21,937	50,942	29,005	136%
SE			±0.1	±00.0	±936	±421	±1142	±3115	±3236	±19%

Notes: Fish productivity values with different superscripts are significantly different at 0.05 level of significance.

profit 136 ± 19% (Table 3).

4.1.4. *Pond and water characteristics*

Across municipalities and clusters, there were significant differences in temperature, pH, colour and Secchi disk visibility of pond water but not in water depth. The deepest depth of water ranged from 0.9 to 1.2 m and the shallowest depth from 0.7 to 0.9 m. Across municipalities, pond water temperature ranged from 26.2 °C (Baucau) to 28.8 °C (Parlamento), with significant differences between them. However, there was no significant difference in pond water temperature between Ermera and Bobonaro (mean: 27.7 °C) (Table 4**)**. In general, across municipalities and clusters, both pond water temperature (range: 26.2–28.8 °C) and pond water pH (range: 6.9–8.6) were in optimal ranges required for tilapia growth. Water colour in all ponds across all locations was mostly between light green and dark green. It was green in Ermera while light green to green in the other three municipalities. Secchi disk visibility of pond water was significantly greater in Lautem and Baucau (42 cm) than in Ermera and Bobonaro (30 cm) (Table 4).

4.1.5. *Effects of household characteristics*

The ponds owned by groups were significantly larger than those owned by individuals, regardless of municipalities and clusters. Besides, ponds owned by male-headed households were significantly larger ($P < 0.05$) than those owned by female-headed households. The male-headed households owning the ponds fed significantly ($P < 0.05$) greater amounts of feed during the 5th month of the production cycle compared to the female-headed households (Table 5). Similar results were found throughout the culture cycle (data not shown). Ponds owned by farmer groups had larger pond area, maintained greater water depth, and fed higher amount of feed compared to those owned by individuals.

Sizes of the earthen ponds were bigger than concrete tanks/ponds due to the higher cost of construction of the latter. Fish farmed in earthen ponds were fed with less feed. Presumably the plankton in green water in ponds supplied abundant nutrients resulting in significantly larger fish in earthen ponds compared to fish farmed in concrete ponds. Farmers practicing integrated agriculture-aquaculture (IAA) systems with vegetables and fruits had larger pond area, used more feed and had

Table 4
Pond depth, water quality parameters, and fish mortality (%) in field trials across municipalities and clusters in Timor-Leste (2020–2022).

Municipality	Cluster No.	Cluster name	Total fish mortality	Pond depth (m)		Water quality parameters (averages)			
			(%)	Deep	Shallow	Temp (°C)	pH	Secchi disc (cm)	Water colour*
Lautem	1	Parlamento	0.60	0.9 ^{x}	0.7^{x}	28.8^{x}	7.9 ^{y}	39 ^{x}	2.4 $^{xy\ cd}$
Baucau	2	Gariuai	1.20	1.2	0.9	25.6	6.9	48	1.4 ^{e}
	3	Ossoguigui	0.60	1.1	0.8	24.8	6.9	55	1.0 ^{e}
	4	Goa7	1.81	1.1	0.8	28.1	7.1	30	2.6 ^{cd}
	Average		1.20	1.1 ^{x}	0.8 ^{x}	26.2^{z}	7.0 ^{z}	44 ^{x}	1.7 ^{z}
	Std.		±0.50	±0.1	±0.1	±1.7	±0.1	±13	±0.8
Ermera	5	Faturquero	0.10	1.0	0.8	28.7	7.5	28	2.7 ^{c}
	6	Laubuno	–	1.0	0.8	29.7	7.6	28	2.5 ^{cd}
	7	Poetete	0.10	1.0	0.8	23.3	7.4	26	4.4 ^{a}
	Average		0.07	1.0 ^{x}	0.8 ^{x}	27.2 ^{xy}	7.5 ^{z}	27 ^{y}	3.2 ^{x}
	Std.		±0.05	±0.0	±0.0	±3.4	±0.1	±1	±1.0
Bobonaro	8	Leohitu	–	1.0	0.8	N/A	N/A	45	2.0 ^{d}
	9	Balibo	–	1.0	0.8	28.1	8.6	38	2.0 ^{d}
	10	Batugade	–	1.0	0.8	28.6	8.0	19	3.8 ^{b}
	Average		–	1.0 ^{x}	0.8 ^{x}	28.3 ^{xy}	8.3 ^{x}	34 ^{y}	2.6 ^{xy}
	Std.		–	±0.0	±0.0	±0.4	±0.4	±13	±1.0
Overall average			0.44	1.0	0.80	27.3	7.5	36	2.5
Standard deviation			±0.36	±0.1	±0.05	±2.2	±0.6	±11	±1.0

Notes: Mean values with different superscripts are significantly different at 0.05. Superscript a, b, c etc. compare among the clusters and x, y, z among the municipalities. *Colours of the pond water are denoted as: 1 clear, 2 – light green, 3 green, 4 dark green and 5 – turbid.

Table 5
Effects of pond ownership, household head's gender, pond and fish types, and whether IAA practiced or not on the pond characteristics, feeding amount, and fish size in field trials across the municipalities and clusters of Timor-Leste (2020–2022).

Description	Group	Pond area (m^2)		Pond length (m)		Pond depth (m)		Fish size at 120th day (g)		5th month feed (g/pond/d)	
		Number of ponds	Pond area (mean)	Number of ponds	Pond length (mean)	Number of ponds	Pond depth (mean)	Number of ponds	Fish size (mean)	Number of ponds	5th month feed (mean)
Pond ownership	Individual	384	106^b	384	13^a	383	0.79^b	380	173^b	384	15^b
	Group	33	142^a	33	14^a	33	0.89^a	33	212^a	33	30^a
Gender	Male	330	113^a	330	13^a	329	0.79^a	328	183^a	330	19^a
	Female	87	93^b	87	12^a	87	0.80^a	85	149^b	87	5^b
Pond type	Earthen	394	112^a	394	13^a	393	0.79^a	391	175^b	394	17^a
	Concrete	23	46^b	23	8^b	23	0.80^a	22	191^a	23	5^b
IAA	With	146	122^a	146	14^a	146	0.79^a	146	196^a	146	18^a
	Without	270	101^b	270	13^a	269	0.79^a	266	165^b	270	15^a
Fish type	GIFT	404	110^a	404	13^a	403	0.79^a	400	175^a	404	16^a
	Others	13	53^b	13	8^b	13	0.78^a	13	189^a	13	0^b
Average±standard deviation		417	108 ± 100	417	13 ± 6.5	416	0.79 ± 0.8	413	176 ± 59	417	16 ± 28

Notes: Mean values with different superscripts are significantly different at 0.05. Superscript a, b, c are to compare among the clusters and x, y, z to compare among the municipalities; IAA = integrated agriculture-aquaculture system.

bigger fish compared to those not practicing IAA. As expected, farmers using monosex GIFT fingerlings had significantly better fish attributes compared to those using mixed-sex GIFT or other fish fingerlings. Among these factors, pond ownership, pond type, gender, and IAA had direct effects on the size of the fish on day 120. Fish grown in ponds and managed by groups were about 18% bigger than those grown and managed by individuals. Ponds managed by male-headed households had 23% bigger fish than those managed by women-headed households and farmers practicing IAA had 19% bigger fish than those not practicing IAA. These results suggest that bigger fish were obtained due to greater amount of feed, and greater amount was given by groups compared to individuals, by male-headed households compared to female-headed ones, and farmers practicing IAA compared to those that do not. In all cases, bigger fish with larger weight were associated directly with the amount of supplementary feeding.

4.1.6. Regression model for the final size of fish

Although 15 predictors were considered to be important in determining final size of the fish, only the following seven predictors were found to be significant ($P < 0.05$). The relationship (intercept and regression coefficients) of the seven significant predictors with the final fish size (sampled at 120th day) can be expressed by the following equation:

$$Y = 168 + 116\times_1 – 7.67\times_2 + 1.08\times_3 – 5.33\times_4 + 0.13\times_5 – 3.68\times_6 + 1.74\times_7$$

Where: 168 = intercept; X_1 = pond deepest depth (m); X_2 = pond water pH; X_3 = pond water colour; X_4 = pond water temperature (°C); X_5 = daily feeding rate in 4th month; X_6 = daily feeding rate in 1st month; X_7 = daily feeding rate in 2nd month.

The intercept of the regression model showed that the size of tilapia reaches about 168 g per piece if no predicting factors (predictors) affect fish size significantly. Among the seven predictors, pond depth (deepest) was the most important determinant of fish size with positive relationship. According to the model, for every unit (meter) increase in pond depth fish size would increase by 116 g, which means every 10 cm increase in pond water depth within the range of 0.7–1.3 m (used in the model) would increase 11.6 g of fish size. The 2nd most important predictor was pH, suggesting that every unit of pH increment (within the pH range of 6.2–8.8) would decrease the body weight of fish by 7.67 g. Colour of the pond water was the third most important predictor which showed positive effect on the fish growth (1.08 g/fish) as colour is the measure of phytoplankton availability. The 4th predictor, temperature, showed inverse relationship with the size of fish. It indicated that every degree Celsius increase in temperature would decrease the final fish size by 5.33 g. The remaining predictors were the daily feeding rates used during 1st 2nd and 4th months. Interestingly, the feeding rate during the first month (X_6) had negative impact on fish growth since they grew only about half of the normally observed weight of 20 g. As a result, fingerlings in the first month were overfed and uneaten feed might have caused deterioration of water quality and consequently negative effect on fish growth.

4.1.7. General discussion on on-farm trials results

Since the farmer clusters in Bobonaro started to organize earliest (i.e., since 2016), and the municipality has relatively plain land, good water availability and warmer climate compared to other municipalities, the largest number of farmers and fishponds were in Bobonaro. Such physical and climatic characteristics are considered to be appropriate for tropical aquaculture. The average pond size in Bobonaro was comparable to that in Viqueque but 68% smaller than in Bobonaro, as reported in a recent study (Salvador et al., 2022). The pond sizes in this trial were smaller as compared to that in Nepal (Bhujel et al., 2008; Farquhar et al., 2019) and in Thailand (Belton et al., 2009). Since Timor-Leste has lot of mountains and hills with very limited arable plain (Timor-Leste Geography & Climate - Tourism Timor-Leste (timorleste.tl), farmers in most areas cannot afford constructing large ponds. In addition to terrain or topography, pond size depends on other factors such as pond ownership. In our study, ponds owned by groups were bigger. This is logical since the group expects higher numbers of fish and income for sharing among its members. The households headed by males had bigger ponds and higher amounts of supplementary feeding compared to the female-headed households. It was learned from the farmers if the ponds are in the backyard they are managed by women but when pond are located at far distant from the homesteads they are managed by male members. Our study suggests a need of training and motivation activities for women to encourage better participation in aquaculture.

On the 120th day of sampling (i.e. through the period where feeds were fully subsidized), Baucau had the largest fish size with highest growth rate (g/fish/day). However, when subsidies were stopped the variation in fish size between clusters was not significant due essentially to the fact that feeding fish with pelleted feed was reduced substantially after the subsidy ended. The fish growth rates in these trials were comparable with those reported in other countries. For example, an average growth rate of 1.0–2.1 g/fish/day was reported in Thailand, where aquaculture is more advanced than in Timor-Leste (Bhujel, 2002a). The larger fish size with high growth rates are possible only when improved strains of Nile tilapia (e.g., GIFT), in the form of monosex fingerlings are used to stock ponds (Bhujel, 2014; Bhujel, 2021). Monosex fingerlings of GIFT have been the first choice of farmers in many countries such as Bangladesh and Thailand due to their faster growth, uniform size fish, and little or no self-recruitment when the proportion of males is 98% or more (Bhujel and Naditrom, 2002; Belton et al., 2009; Baqui and Bhujel, 2011).

In general, the average size and daily growth rate of the fish in Baucau and Lautem were higher than in Ermera and Bobonaro due to the continuation of feeding high quality commercial feed pellets beyond 120 days post-stocking. Farmers in Baucau and Lautem continued purchasing and feeding higher amount of feed while those in Ermera and Bobonaro used less pelleted feed after the subsidy was ceased after the 4th month. Farmers in Bobonaro purchased and fed a very limited amount of feed in the 5th and 6th months and those in Ermera did not buy or feed at all. This indicates that farmers in Baucau and Lautem are more enthusiastic in farming fish as aquaculture business even if they need to buy feed, so it is likely to sustain and grow in these municipalities. It is a common belief in aquaculture that more the feed that is given to fish, the better would be the growth. Use of quality feed based on a combination of local ingredients and imported feed pellets would be important for success of GIFT aquaculture for farmers practicing subsistence farming systems (Pant et al., 2023a).

The overall average GIFT yield obtained in this study (12.4 $\pm$ 0.1 t/ha/180-day cycle) was 53% higher (8.1 t/ha) than reported in Bangladesh (Tran et al., 2021), where the aquaculture industry is well developed. In our study, the fish productivity in the second phase of the project was nearly 300% higher (yield range: 4.2 to 12.4 t/ha/180-day cycle) than that in the previous phase and culture period was reduced from 11 to 6 months. In the first phase, farmers prepared feed from locally available ingredients with less than $\leq$18% CP whereas in the second phase, they used imported floating pellets with 29–34% CP. Therefore, higher fish productivity was realized mainly due to the use of high-quality feed fed following an adequate feeding rate and feeding schedule. Availability of good quality water was another factor contributing to high yield, especially in Lautem and Baucau. As mentioned earlier, farmers in these municipalities continued to maintain green water rich in natural food for fish and fed throughout the 5th and 6th months by purchasing pelleted feed themselves, even after the project stopped providing subsidy. Continued feeding as per the feeding schedule even after cessation of the subsidy resulted in about 26% higher fish productivity in these municipalities as compared to Ermera and about 34% compared to Bobonaro. These results suggest that water availability and access to high quality feed are major factors for enhanced GIFT productivity. However, there is still potential to increase productivity further by increasing stocking density, applying better feeding management, providing aeration, better fertilization, and night-time lighting (Ng et al., 2013; Bhujel, 2002b; Bhujel, 2014).

4.2. Feed supply and feed management

Farmed tilapia can be raised using commercial or farm-made feed, or with natural food (phytoplanktons or zooplanktons) in green water (Ng et al., 2013; Bhujel, 2014; Pant et al., 2023a). For small-scale poor farmers, a combination of feed containing high protein content and pond fertilization is recommended as this would increase fish growth rate, and thereby productivity, while keeping input costs relatively low. Depending on cost and availability, fish can be fed with floating or sinking pellets, or farm made feed using locally available ingredients. Corn meal, rice bran, leucaena leaf meal, taro leaf meal, and cassava are plant-based ingredients for on-farm preparation of feed (Bhujel, 2014; Pant et al., 2023a). The leaves and fruits of the trembesi plant, and leaves of moringa and cassava plants can also be used as raw materials for fish feed (Jusadi, 2019). Jusadi (2019) recommended feed containing 29% corn meal and 60% taro leaf meal for small-scale farmers of Timor-Leste considering the protein content, feed price, and the presence of omega 3 fatty acids.

Using a feed conversion ratio (FCR) of 1.5, an estimated 18,000 tons of high-quality feed/year would be needed by 2030 to meet the NADS's target of 12,000 tons of fish production (NDFA-MAF, 2012b; Pant et al., 2020a). Reaching this target would ideally require the establishment of more small to medium feed manufacturing enterprises, using combinations of locally available and imported ingredients. Establishing feed mills and producing a large quantity of pelletized feed, however, is not feasible due to the shortage of raw ingredients in the country (Pant et al., 2023a). Hence, until the country has a sufficient supply of feed ingredients, importing high quality feed in bulk and establishing an efficient marketing and distribution system becomes vital for integrating GIFT aquaculture in small-scale subsistence farming systems and its scaling across the country. This will ensure that there is enough feed available at relatively low costs to farmers in rural areas.

WorldFish in partnership with the Ministry of Agriculture and Fisheries, Timor-Leste are trying to address marketing constraints by importing a few key feed ingredients and commercial fish feed pellets in bulk to facilitate intensification of GIFT aquaculture. Selected feed importers have been offered the opportunity to grow their businesses by connecting them with fish farmer networks. LSPs are facilitating the linkages among farmers, input suppliers and output markets. The possibility of establishing an in-country feed plant is also being explored. The viability of local commercial feed manufacture is being explored and will depend primarily on price and importation of feed ingredients (fish meal, soyabean meal, mineral, vitamin mixes, etc.) (Sendall et al., 2022).

Timor-Leste's current low demand for fish feed might constrain the economic viability of an in-country feed manufacturing sector. Therefore, supporting private sector importation of high-quality feed in bulk may serve as an alternative for scaling of aquaculture in a more efficient and cost-effective way until the time when the Timor-Leste starts producing feed itself (Pant et al., 2023a).

Globally, aquaculture producers have been reducing the use of fishmeal and fish oil in feed formulations, and these efforts have been reinforced by sustainability goals throughout the supply chain. Fishmeal and fish oil remain important ingredients of fish feed supplying essential nutrients to support larval and fry performance and survival, but are now used in very small amounts for grow-out and broodstock fish. In recent years, attempts have been made elsewhere to explore alternatives to fishmeal or soybean meal to enhance the quality of feed, which have emerged as potential sources of protein, such as black soldier fly and other insect meals (Bhujel and Perera, 2023; Galecki and Golaszeweski, 2023). These alternatives may also work in homestead small-scale production systems. Future studies may consider addressing the technical feasibility, economic viability and environmental aspects of the mass-scale production of fishmeal alternatives in Timor-Leste.

4.3. Capacity building and training

The PADTL project has been providing institutional support to NDA-MALFF and government hatchery staff at various levels. The continuous mentoring of NDA staff both at central and local levels has resulted in notable improvements in their knowledge and skill in both hatchery and grow-out systems. This is reflected in the increased survival of eggs and fry at the public hatchery; regular update of hatchery database by the staff with minimal support; and active participation of local level NDA staff as co-facilitators in FFS training. Training is now being designed and delivered unaided by the staff of the NDA-MALFFF's Hatchery Department. NDA staff have also delivered a specialized training on GIFT hatchery and grow-out technologies to international participants from Solomon Islands and Fiji in 2018 and 2019.

Training and capacity building of farmers and various stakeholders, including private sector partners (hatcheries, nursery operators, and LSPs), is crucial for building knowledge on sustainable aquaculture production, intensification and scaling of seed, feed, and grow-out technologies. Modular training on tilapia aquaculture following the FFS approach – a group-based learning using participatory tools and techniques – has been useful in delivering BMPs to nursery operators and grow-out farmers. A total of 1634 farmers, nursery operators and LSPs, and hatchery staff (25% women) across ten clusters in four municipalities have successfully completed various types of trainings (Table 6).

4.4. Communication, technology dissemination and scaling activities

Various types of local and English language knowledge products (e.g., manuals, illustrated guides, posters, banners, or graphics on seed, feed, grow-out technologies, clinical signs, nutrition) have been developed and disseminated widely to national and international audiences through the PADTL project. These materials are widely used by stakeholders for scaling sustainable aquaculture technologies across Timor-Leste and are now also being adopted in the Solomon Islands and Fiji. Aquaculture promotional activities, such as fish harvesting ceremonies and farmer exchange visits to fishponds, are organized annually, and key successes are highlighted through national and international media (e.g., the Fish site, Hatchery International Magazine, Inter Press Service (IPS), national newspapers and television channels). The national aquaculture forum organized every 2–3 years and the conference proceedings have provided networking and partnerships building opportunities and for communication and dissemination of aquaculture technologies. The manual "Better Management Practices (BMPs) for genetically improved farmed tilapia in Timor-Leste" in both English and local languages and its distribution to fish farmers and various stakeholders has proved to be very useful (Pant et al., 2019c). Another manual, "BMPs for monosex tilapia seed production: An "Illustrated Guide" (Pant et al., 2020b), intended for government, I/NGOs and private sectors involved in tilapia seed production and grow-out systems, has been useful not only in Timor-Leste but also in other island nations across the Asia-Pacific region. The Nutrition Poster, "Put tilapia on your plate and you will stay healthy" provides nutritional benefits of tilapia for rural farmers and consumers in simple visual diagrams.

4.5. Partnership building activities

Partnerships have been forged at various levels, encompassing farmers and grassroots organizations to the private sector, I/NGOs, and federal ministries. These collaborations aim to achieve the NADS target for fish production and consumption through aquaculture. For examples, Memorandum of Agreements (MoAs) have been signed with 10 cluster leaders, a feed importer, three market operators and seven Local Service Providers (LSPs), four private hatcheries, and eight GIFT nurseries. Five other nurseries, supported by other I/NGOs, were also provided with technical advice and training from the PADTL. However, there is a need for more hatcheries, nurseries, LSPs, and market operators across the country to scale aquaculture sustainably.

4.6. Developing markets

In order to significantly increase fish consumption by common people as part of their regular diet, production must be increased, and fish price reduced. In addition to fish consumption by local people in rural areas, either by farming or by buying fish, there are also fish demands from education and health sectors. Hence, improved marketing through better linkages between rural producers and retailers in urban centres is needed. The target market will be institutional buyers, such as for use in school feeding programmes and in hospitals and health care centres. This will require focusing on the areas of highest urban populations and supporting GIFT production close to the municipal capitals. Closer proximity to municipal capitals will also provide for easier access to commercial fish feed suppliers.

Currently, nearly 80% of the fish produced in Timor-Leste is sold informally by the small-scale fishers/farmers directly to local rural consumers, 16% to small retailers in local municipal markets, and the remaining 4% to a single intermediary trader who supplies fish to a supermarket in Dili (Sendall et al., 2022). Small-scale farmers can organize in groups/clusters to achieve better efficiency in marketing. Farmer groups, compared to individuals, can purchase quality farm inputs at cheaper prices and thus reduce production costs. Likewise,

Table 6
Summary of trainings and cluster meetings organized during October 2021 – March 2023 across municipalities and clusters in Timor-Leste.

Month-Year	Municipalities	No. of trainings	Clusters	Topic	Total participants	Male	Female	% Female
Oct-Nov 2021	All 4 municipalities	5	5 clusters	Discuss on MoA & Planning	70	49	21	30%
Oct, 2021	Ermera & Bobonaro	3	Laubonu, Leohitu, Balibo	Pond renovation and preparation	41	34	7	17%
Oct-Dec 2021	All 4 municipalities	10	All ten clusters	Fry restocking & feeding	129	109	20	16%
Jan-Feb, 2022	All 4 municipalities	10	All ten clusters	Water quality, fertilization	122	94	28	23%
Jan-Mar, 2022	All 4 municipalities	10	All ten clusters	Planning, Data record, feed, seed	142	110	32	23%
Feb-Mar, 2022	Baucau, Bobonaro, Lautem	4	4 clusters	Sampling, nursing & harvesting	48	39	9	19%
Jun, 2022	Dili	1	From all hatcheries	Hatchery operation	13	13	0	0%
Jun, 2022	Dili	1	From clusters	Role of LSPs, feed importers & market	14	13	1	7%
Jun, 2022	Dili	1	From clusters	Training of trainers (ToT) - Grow-out	16	14	2	13%
Jun-Sep, 2022	All 4 municipalities	11	All ten clusters	Project meeting, discussion	151	136	15	10%
Jul-Aug, 2022	Baucau, Bobonaro, Ermera	8	9 clusters	Fish harvesting & marketing	602	401	201	33%
Sep, 2022	Ermera	2	Laubonu & Fatuquero	Pond renovation and preparation	24	22	2	8%
Nov, 2022	Dili	1	From all ten clusters	Role of LSPs, feed importers & market	10	8	2	20%
Jan-Mar, 2023	All 4 municipalities	9	9 clusters	Feeding & water quality management	145	111	34	23%
Jan-Mar, 2023	All 4 municipalities	7	9 clusters	Agreement, planning for seed & feed	107	78	29	27%
	Total	83			1634	1231	403	25%

farmer groups can join together to sell their fish at a better price. Responsible and successful farmer groups will also be attracted to the banking and insurance sectors for obtaining credit and fish harvest insurance, thereby reducing the financial burden and risk on fish farmers.

The findings of the recent aquaculture value chain and market analysis study indicated that the modest amounts of fish from the partial harvests are readily sold at the pond sides or at nearby local markets, and thus marketing of the fish under the current low production scenario has not been an issue (Sendall et al., 2022). However, when fish farmers and aquaculture area will increase, the production volume will also increase. Hence, there is a need to establish strong linkages between farmers' clusters and the supermarkets in Dili and other major towns in different municipalities and develop MoUs with MALFF (former MAF) and potential development partners and donors. The PADTL project is working as a facilitator to connect fish farmer clusters to sell live fish in Dili and other major towns to provide further avenues for farmers market fish. It is anticipated that a dual-pronged approach of increasing production with imported commercial feed and improving market linkages to urban centres will significantly increase post-farm gate sales.

4.7. *Scaling and sustainability of aquaculture*

Mechanisms for GIFT seed production and distribution through the PPP model, nursery raising and distributing fingerlings to farmers, expanding grow-out farming, and establishing markets for fish are now in place. The technical capacity of public and private hatchery staff has been improved, farmers have been trained, and LSPs have been trained to supply inputs (fingerlings & feed) and assist farmers in marketing of fish. Regular consultation and joint monitoring of fish farmers and stakeholders across Timor-Leste is organized as part of project interventions and government responsibility. Hence, with concerted effort, rapid aquaculture development can occur, as has been experienced in other Asian countries with small-scale subsistence farming, for e.g., Nepal (Shrestha et al., 2022). Equally, there is concern that this growth in aquaculture will not eventuate if financial and technical support to hatcheries, grow-out farmers and nursery operators is discontinued. Continued mentoring and refresher trainings with a view to further strengthening hatchery staff skills and knowledge to run hatcheries in full capacity would be crucial to addressing these concerns. Likewise, technical supervision and strengthening of farmer groups/clusters is also crucial for enabling them to cope with the risks associated with production and marketing. Further expansion of seed and feed production systems through the PPP model will be vital for scaling and sustaining GIFT aquaculture in the subsistence farming systems in Timor-Leste's inlands (Pant et al., 2023b).

Further intensification needs to be carefully thought and planned because global aquaculture has been facing some serious challenges as the large-scale commercial aquaculture is considered to be an unsustainable activity due to excessive amount of effluents discharged to the environment which contain high levels of organic matter, nitrogenous compounds, toxic metabolites, and elevated rates of chemical and biochemical oxygen demands (Emerenciano et al., 2017). Other criticisms of commercial aquaculture include competition for land and water with other users, introduction of exotic species, overexploitation of ocean fish stocks for fish meal and fish oil production, spread of pathogens, and development of antimicrobial resistance. Furthermore, high stocking densities and increased demand for water, feed and fertilizers that is associated with aquaculture intensification can also lead to increased waste production (Beveridge et al., 2013). Besides, commercial aquaculture is faced with other challenges such as shortage of feed ingredients and their price volatility (Emerenciano et al., 2017). However, it is unlikely that aquaculture farmers in Timor-Leste will face such problems, as the aquaculture development model promoted by the PADTL includes small-scale semi-intensive production systems. These systems rely on the maintenance of green water in combination with supplementary feeding using commercial feed pellets, which is carefully adjusted monthly based on the total fish biomass in the pond.

5. Conclusions and future potentials

The participatory on-farm trials using 417 ponds and involving 169 farmers demonstrated that small-scale inland freshwater aquaculture is technically, economically, environmentally and socially viable across Timor-Leste. An average yield of 12.4 ± 0.1 t/ha/180-day cycle can be achieved using small ponds 105 ± 34 m^2 (range: 53–164 m^2) by stocking about 540 fingerlings (5 fingerlings/m^2) and with about 200 kg of feed. A farmer could harvest 260 ± 20 g fish by the 6th month with a gross profit of US$29,026 ± 3233/ha, i.e., 136% of the variable costs (seed, feed and labour), which should encourage uptake and expansion of the sector in Timor-Leste. Farmers could potentially have two grow-out cycles in a year, the gross profit of which would cover two thirds of the income required to raise family income above the poverty line, i.e., US$2.15 per day (World Bank, 2021).

Assuming two grow-out cycles per year, over 320 ha of pond area and 30 million fingerlings would be required to achieve the NADS target of 8000 metric tons of tilapia/year through inland freshwater aquaculture (i.e., two thirds of total aquaculture production) by 2030 to solve Timor-Leste's malnutrition problem **(**NDFA-MAF, 2012b**)**. To achieve such a highly ambitious target, massive expansion of aquaculture is needed. Importantly, this would require technical capacity of the current hatcheries to be enhanced and an additional 6–8 PPP model hatcheries established and operated at full capacity by 2030 as described in Pant et al. (2023b).

In achieving this success in Timor-Leste, several lessons have been learned, such as:

- Aquaculture intervention can be successful and impactful if the right strategies and clear goals are established, and policies and plans are aligned with them.
- Formation of groups or clusters is important for the effective adoption of aquaculture technologies as the farmers can learn from each other to solve their problems by themselves.
- Farmers learn about aquaculture techniques and improve their management skills gradually to increase efficiency thereby enhance productivity.
- Pond productivity can be increased by over 300% if the right species and right technologies are chosen by making quality seed and feed easily accessible.
- Small-scale aquaculture can be viable and contribute to food and nutrition security of the people if they are organized in clusters.
- Well-coordinated actions are required along with continuous technical supports and partnerships between public and private sectors.
- This successful model could be replicated in other countries with similar contexts especially the small island developing states (SIDS).

CRediT authorship contribution statement

Jharendu Pant: Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing. **Shwu Jiau Teoh:** Data curation, Project administration, Validation, Visualization. **Silvino Gomes:** Methodology. **Angelo Pereira:** Methodology. **Mario Pereira:** Methodology. **Lucas Soares de Jesus:** Methodology. **Adriano Dani F. Du Carmu:** Methodology. **Ram C. Bhujel:** Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing.

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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