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Sustainable production and dissemination of genetically improved farmed tilapia seed in smallholder farming systems: A case study from Timor-Leste

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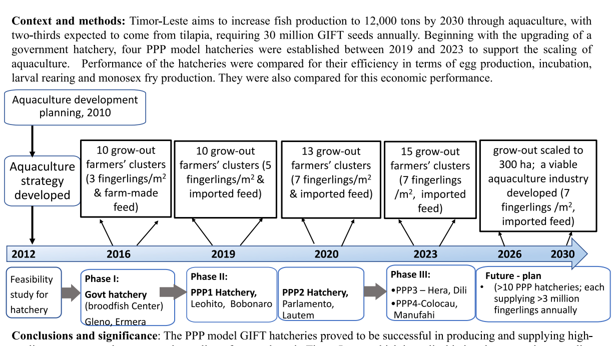
HIGHLIGHTS

- Timor-Leste aims to increase aquaculture production to 12,000 tons by 2030, with two-thirds from tilapia.
- The integration of aquaculture into existing subsistence farming systems is important for diversifying rural livelihoods.
- Public and Public-Private Partnership (PPP) model GIFT hatcheries were developed for producing high-quality fingerlings sustainably.
- Hatcheries' performance was evaluated by comparing weekly data on eggs, clutch size, incubation, swim-up fry, monosex fry.
- The PPP model hatcheries can be scaled to countries with similar agroecological and socioeconomic context as Timor-Leste.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Timor-Leste's National Aquaculture Development Strategy (NADS) 2012–30 aims to achieve an annual aquaculture production of 12,000 tons by 2030 to raise per capita fish consumption from 6.1 kg in 2010 to 15 kg. Genetically Improved Farmed Tilapia (GIFT) is identified as the most suitable species under Timor-Leste's existing farming systems and agro-ecological context. It is expected to account for two-thirds of total aquaculture production, requiring over 30 million fingerlings annually, necessitating a strong role of public and private sectors to develop a sustainable hatchery model for producing and supplying high quality GIFT fingerlings to fish farmers on a mass-scale.

OBJECTIVE: The major objective was to conceptualize and apply a public-private partnership (PPP) model to produce and disseminate high-quality monosex GIFT seed by public and private hatcheries across Timor-Leste.

METHODS: Model GIFT hatcheries were established and monitored using a standard protocol developed by the R&D team. Data on total eggs, clutch size, incubation survival rate, swim-up fry, and monosex fry produced were recorded on a weekly basis. The performance of hatcheries was compared using descriptive statistics at a 5%

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level of significance. Economic analysis was conducted to compare production costs, gross profits, and net profits among hatcheries and nurseries. Enabling conditions and factors for effective PPP were identified.
RESULTS AND CONCLUSIONS: The WorldFish, in collaboration with Timor-Leste's Ministry of Agriculture and Fisheries, upgraded an existing public hatchery in Gleno, Ermera, introduced GIFT in 2015, and developed it as a GIFT broodstock centre to supply quality brood fry to other hatcheries. To produce monosex seed on a mass-scale, four PPP model GIFT hatcheries were established between 2019 and 2023. Results from a public hatchery and two initially established PPP model hatcheries showed that the hatchery in Parlamento had significantly higher ($P < 0.05$) monthly production of eggs, swim-up fry, monosex fry, and clutch sizes. On average, over 177,000 monosex fry per month were produced by those three hatcheries. Local service providers (LSPs), self-employed youths who have been recruited and trained to facilitate input supply and output marketing, purchase GIFT fry from the hatcheries, nurse them to fingerling size, and supply them to farmers. To achieve high seed production and supply targets, scaling of PPP model hatcheries, nurseries, and LSPs along with effective training and technical back-up, favourable policies, institutional environments, and governance mechanisms, is necessary.
SIGNIFICANCE: The PPP model GIFT hatcheries are scalable across inland farming systems in Timor-Leste and other countries with similar agro-ecological, socio-economic, and climatic contexts.

1. Introduction

Farming systems in small island nations predominantly comprise of cropping, livestock raising, and fishing and aquaculture activities. In the coastal areas, marine or coastal fishing and aquaculture become the main components of farming systems while in low-lying inlands and mountains away from the coast, cropping, poultry and livestock rearing activities dominate the systems though fishing in rivers and lakes and aquaculture can significantly contribute to household food and nutrition security and farmers' livelihoods (Georgeou et al., 2022; Robins et al., 2020). Recent trends and evidence show that the farming systems in the coastal areas are vulnerable to climate change effects and consequent sea level rise and flooding, while those in the inland areas are vulnerable to erratic rainfall and consequent drought or flooding and to increased temperatures (Barange et al., 2018; Bell et al., 2011; Pickering et al., 2011). Diversification of farming-based livelihoods is vital to maintaining ecosystem resilience and building social systems resilience. There is growing appreciation of the of role of aquaculture in diversification of livelihood options and thereby increasing adaptation and resilience to climate change in both coastal and inland areas (Barange et al., 2018; Dey et al., 2016; Rosegrant et al., 2016). Integration of aquaculture in crop-based farming systems, especially in inlands, has potential to play a significant role in improving food and nutrition security and income of farmers (Robins et al., 2020). The provision of viable technology, quality inputs (seed, feed), and quality services (market, extension) are prerequisites for the development of sustainable aquaculture. Of all, seed is the most critical input and the availability of and access to high-quality seed by farmers in the context of small-scale, resource-poor farming systems is vital for scaling aquaculture sustainably (Pant et al., 2023a, 2023b).

It has been well recognised that the involvement of both public and private sectors in a complementary and synergistic mode would be necessary to produce high quality fish seed in a mass-scale and meet the fingerlings and fish production targets of any country. A system where public and private sectors work together for the common goal follows the public-private partnership (PPP) model (Bjärstig, 2017). Under such scheme, the PPP is set out in an agreement outlining the responsibilities of each party (Weirowski and Hall, 2008; Weirowski and Liee, 2010; Murekezi et al., 2018). The PPP model in agriculture and aquaculture has been successfully applied across the globe including countries in South and Southeast Asia (Acosta et al., 2006; Weirowski and Hall, 2008; Weirowski and Liee, 2010; Baqui and Bhujel, 2011; Bhujel, 2011; FAO, 2016a; FAO, 2016b; Sinha et al., 2016; Murekezi et al., 2018).

Timor-Leste (or East Timor) is a small half-island nation located in the north of Darwin, Australia and east of West Timor of Indonesia. It has a coastline of 730 km and population of 1.3 million, with the forecast of approaching 2 million by 2030 (WFP, 2022; Steenbergen et al., 2019). The country is characterised by high level of poverty (42%) and malnutrition (child stunting, 58%; underweight, 60%; wasting, 26%) (Andersen et al., 2013; CWW, 2022). Over 60% of its population is affected by chronic food insecurity, especially from September to April in uplands and mountains and during the months prior to harvest of maize or rice in northern and southern lowlands (da Costa et al., 2012; López-Angarita et al., 2019) and hidden hunger due to the deficiency of essential micronutrients in the regular diet (da Costa et al., 2012). It truly represents the small island developing states (SIDS) with similar geography, farming or fishing systems, poverty and malnutrition, and vulnerability to climate change.

Although Timor-Leste is surrounded by the sea, its artisanal capture fisheries, which uses small boats and basic fishing gear, result in very small catches. Most of the fish are caught near the shore, with approximately 75% of the total catch being consumed fresh (FAO, 2022). Thus, fish caught from the sea hardly reach inland areas in desired size and quality due to extreme topography and the lack of good infrastructure for transport, storage, and post-harvest handling. Fisheries and food security analyses have also revealed that the major constraints for consumption of fish in country's inlands are inaccessibility, unavailability and unaffordability (AMSAT International, 2011; Andrew et al., 2011; Andersen et al., 2013). Considering the rapid growth of aquaculture in Asia and its increasing contribution to improving food and nutrition security of people and nations' economy (FAO, 2022; Naylor et al., 2020; World Bank, 2013), it is realized that this sector has such potential in Timor Leste too (DRTL, 2017; NDFA-MAF, 2012a). However, the provision of access to and availability of quality seed was realized as prerequisite for aquaculture development. A PPP model, fostering complementarity between the government and the private sector, would facilitate the mass-scale production of fish seed or fingerlings and their distribution to fish farmers in rural and inland areas. This approach would promote the sustainable scaling of aquaculture into the existing farming systems across the country and could effectively tackle the country's chronic malnutrition problem.

Of all the fish species, tilapias are the second most cultured species group by volume after carp (Tveteras et al., 2019). Nile tilapia (*Oreochromis niloticus*), together with its hybrids, is produced over seven million metric tons annually from low input ponds to highly intensified cages and tanks in over 100 countries (El-Sayed, 2006; Bhujel, 2014; Bhujel and Suharman, 2021). It is an omnivorous fish suited for resource-poor farmers due to its ability to tolerate low dissolved oxygen levels and feed on phytoplanktons, periphytons, aquatic macrophytes, benthic invertebrates, detritus, thus reducing the need for high amount of added feed (Bhujel, 2014). It has a relatively short culture cycle (5–6 months) allowing farmers to harvest two crops in a year. Hence, it can be an ideal species for inland aquaculture due to its low price, low in food chain, availability of improved broods and seed production practices, and its expanding business. Genetically improved farmed tilapia (GIFT), developed by WorldFish through selective breeding, is a fast-growing, hardy and resilient strain of Nile tilapia (Eknath et al., 2007; Ponzoni et al., 2011). GIFT has adapted well and performed superior to other tilapias across tropical environments in Asia and Africa (ICLARM-UNDP, 1998; ADB, 2005; Tran et al., 2021; Moses et al., 2021), and has great potential for Timor-Leste and other small island developing states (SIDS).

Combating poverty and malnutrition by increasing fish production and consumption has now been the topmost priority of the Timor-Leste Government. This is reflected in its National Aquaculture Development Strategy (NADS), where the government has a target to increase national per capita fish consumption from 6.1 kg in 2012 to 15 kg by 2030 by increasing domestic fish production to 30,000 tons annually, 12,000 tons (40%) of which is expected to contribute by aquaculture (NDFA-MAF, 2012b). Further, 2/3rd of production (i.e. 8000 tons) through aquaculture is expected to come from tilapia culture alone and remaining 1/3rd through other species. To meet the above production target through aquaculture, over 10 privately-owned hatcheries with an annual seed production capacity of 3–5 million would be required to produce approximately 30 million monosex tilapia fingerlings annually. For production of a large number of fingerlings, a PPP model can be used in which the government hatchery can maintain genetic quality and produce quality broodstock for supply to private hatcheries, which in turn can produce monosex tilapia seed for supply to nursery operators and grow-out farmers across the country (Pant et al., 2023a, 2023b).

Under the above context, WorldFish began collaborating with Timor-Leste's Ministry of Agriculture and Fisheries (MAF) in 2014 through the New Zealand government-supported Partnership for Aquaculture Development in Timor-Leste (PADTL) project. One of the objectives of the project was to establish a scalable model for sustainably producing and supplying quality GIFT seeds to farmers by applying a PPP model suitable for the farming systems and agro-ecological context of Timor-Leste (Little et al., 1997; Little and Hulata, 2000; Bhujel, 2011; Bhujel and Woollard, 2011; Pant et al., 2020b). Such a model for producing the tilapia seed in mass-scale and supplying them to farmers has been successfully applied in Asia especially in Bangladesh, Thailand and the Philippines (Acosta et al., 2006). A decade of WorldFish experience and in particular the last four year's project interventions has offered valuable lessons to the government, development partners, researchers and field technicians, and aquaculture farmers (Pant et al., 2023a, 2023b), but peer review literature is lacking to share such experiences. Thus, the overarching objective of this study was to document the hatchery development approaches and implementation processes which could be useful for scaling aquaculture in the country and could also be applied to other sub-sectors of agriculture. The specific objectives were to highlight the process of monosex seed production and its specialized techniques, present seed demand and supply status and trends; compare the performance of different hatcheries; identify the problems, constraints and opportunities in implementing the model; and provide recommendations for the government, development partners and private sectors for development of sustainable aquaculture. It is also envisioned that such a model could be applicable to other countries especially the small-island developing states (SIDS) with rapid population growth, high level of poverty and malnutrition, and similar agro-ecological, climatic, farming systems, and socio-economic characteristics.

2. Methodology, approaches, and processes

2.1. Public-private partnership model

Unlike many countries where the private sector can independently operate the hatchery business, the private sector in Timor-Leste is still in its infancy and requires continuous technical guidance and support. Through the provisioning of high-quality broodfish and technology support from public hatcheries, private sector hatcheries can produce high-quality seed to meet the demand for fingerlings. In this study, the main public sector partner in the PPP model for seed production and supply is the MAF who owns the public hatchery and provides quality broodstock and technical advice to private hatcheries and farmers. The main private sector partners at the municipality level are the hatchery owners who produce and supply GIFT monosex seed. The field-level partners are nursery operators/farmers who nurse monosex fry to grow bigger size to fingerlings and supply to grow-out farmers who are organised in various clusters and participate in on-farm trials and demonstrations and produce fish in various municipalities for their own consumption and sale. The nursery operators purchase GIFT monosex fry (<1 g) mostly from the PPP model hatcheries and nurse them in tanks or hapas for 4–6 weeks to achieve desired fingerling size (5-10 g) and then sell to farmers either locally or to other villages/municipalities. Partnership agreements between WorldFish and MAF and with each of the private hatcheries, individuals, or groups have been signed outlining their roles and responsibilities. These agreements outline that the private sector has received significant support from the project and the MAF, and in return, the hatcheries will supply fingerlings at a modest price to help achieve the country's aquaculture production target. The PPP model showing various public and private sector partners for GIFT seed production and supply is shown in Fig. 1.

2.2. Hatchery development process

Prior to the start of the PADTL project, a feasibility study was conducted in 2012 to select a public hatchery suitable for rotational breeding of cohorts and maintaining the GIFT broodstock. The government hatchery at Gleno in Ermera municipality was selected for this purpose due to its favourable climatic conditions, good water supply source, and proximity to Dili with easier access. The hatchery construction was completed in late 2015, followed by introduction of four cohorts of GIFT broods, rotational breeding of GIFT cohorts, and production of monosex fry from early 2016. However, it was realized that the government hatchery with limited capacity and space was not adequate to produce GIFT seed in a mass scale. Private sector's engagement was realized, and potential sites were explored towards the end of Phase 1. The site was chosen based on the farmer's willingness to establish a hatchery, existing farm ponds, experience in fish farming, favourable temperature, all the year round water availability, and a suitable area for scaling tilapia farming across the municipality. The hatchery construction started in the early 2019 and operation began in the same year.

The project team was exploring more sites for new hatchery constructions and a site in Parlamento in Lautem municipality was selected in early December 2019. Soon after that, the second PPP model hatchery was constructed, which started producing monosex fry from 2021 despite the COVID-19 induced movement restrictions and lockdowns in 2020. When restrictions and lockdowns were lifted out, a new phase of hatchery development took its momentum. Agreements were signed to establish two new PPP model hatcheries in Hera in Dili municipality and Colocau in Manufahi municipality in 2022 which started their operations from early 2023. All five hatcheries are following better management practices for seed production developed by WorldFish (Pant et al., 2020a). The government hatchery in Clacuc is currently being developed as a broodfish center to serve as a backup hatchery to Gleno, while the establishment of a new PPP model hatchery in Baucau is under consideration. In order to meet the target of producing 30 million fingerlings annually by 2030, all the existing hatcheries need to operate in full capacity, each producing around 3–5 million fingerlings annually, or increase the number of hatcheries to over 10. The spread of the hatcheries in different locations is strategically important for effective dissemination of GIFT seed and scaling up of the aquaculture technologies across the country (Fig. 2).

2.3. General description of hatcheries

Latitude and longitude using a global position system (GPS) device,

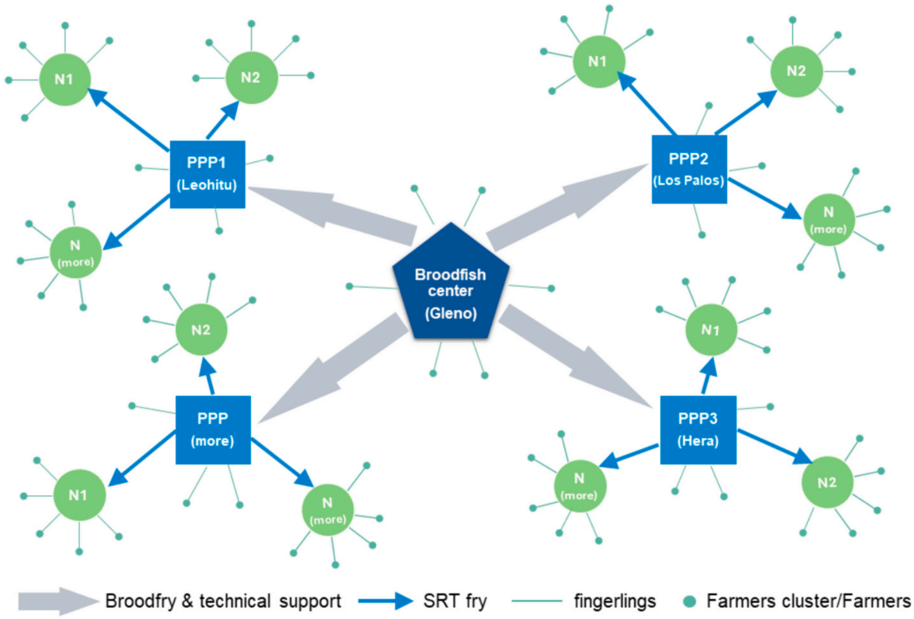

Fig. 1. Schematic diagram illustrating PPP model for GIFT seed production and dissemination in Timor-Leste. PPP = Public-Private Partnership model hatchery; N = nursery.

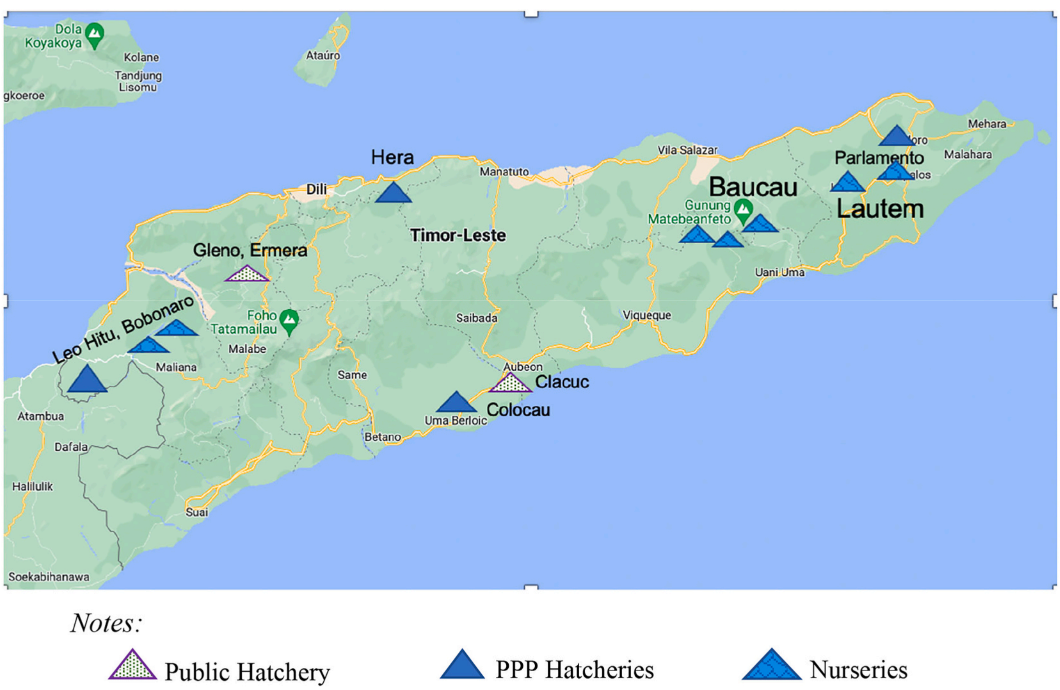

Fig. 2. Locations of the public and PPP model GIFT hatcheries and nurseries across various municipalities in Timor-Leste.

and water temperatures of the incubators and ponds of the hatcheries in Gleno, Leohito and Parlamento were recorded. The GPS showed that all hatcheries are located within the narrow range of latitude and longitude. Likewise, there were little differences in pond water temperatures across the sites (Table 1). The water temperature was relatively higher in Parlamento where water temperature in incubators did not fall below 22 °C whereas in Gleno and Leohito temperatures were as low as 19 °C and 18 °C, respectively. In Gleno and Parlamento, the lowest water temperatures in brood ponds and tanks were 24 °C and 25 °C, respectively, which are ideal for tilapia broods for spawning. In Leohito, however, the water temperatures occasionally lowered to 20 °C, which might have impeded feeding and breeding activities to some extent (Bhujel, 2014; Bhujel et al., 2001b). In the broodstock pond at Gleno Hatchery, DO levels averaged 3.0 ± 0.2 ppm in the morning (6 am) and increased to 12.3 ± 0.3 ppm by the afternoon. The pH ranged from 6.2 to 8.2. However, due to limited laboratory equipment and technical expertise of hatchery staff, other water quality parameters were not assessed. Similarly, in two other hatcheries, measuring both DO and pH was not possible due to the same limitations.

All hatcheries have a building including incubation jars and trays, a water filtration system, storage facilities for materials and equipment, and a number of earthen or concrete ponds for breeding, sex-reversal

Table 1
GPS coordinates, and average water temperature (°C) of incubators and fishponds of the hatcheries in Timor-Leste.

		Gleno	Leohito	Parlamento
GPS Location	Latitude	-8.72°	-9.00°	−8.35°
	Longitude	125.44°	125.06°	126.94°
Water temperature	Incubators			
	Average	23.0	24.9	25.8
	SD	2.7	1.2	1.4
	Range	19–26	18–27	22–29
	Ponds/tanks			
	Average	26.0	27.2	27.6
	SD	1.9	1.1	2.4
	Range	24–28	20–31	25–31

treatment, and nursing. Broodfish are raised in nylon net hapas measuring 8 m × 5 m× 0.9 m in all hatcheries, with each hapa stocked with 200 female and 150 male broodfish, maintaining a female-to-male ratio of 2:1.5. Sex reversal treatment and nursing are done in smaller hapas measuring 3 m × 2 m × 0.9 m and 5 m × 2 m × 0.9 m, respectively. Each hatchery has a standard incubation facility with the capacity to accommodate 30–60 jars or trays, a storage facility for materials and equipment, and a multipurpose room for an office and accommodation of staff during night duty. Sand-gravel water filtration system is used to filter and recycle water to incubation jars and trays. Additionally, each hatchery has storage facilities for hapas and feed (Fig. 3). All hatcheries follow standard better management practices (BMP) guidelines for monosex tilapia seed production (Pant et al., 2020b). Senior level technical and management staff from all hatcheries have received international tilapia hatchery technology training in Thailand, while all staff are regularly trained and mentored by PADTL project in the country. All hatcheries are connected with one or more nurseries that receive GIFT monosex fry from hatcheries, nurse them to fingerling size, and sell them to the fish farmers in their areas.

2.3.1. Public hatchery: Gleno, Ermera

This hatchery is located at 41 km south-west of Dili (Fig. 2). The hatchery was established by the government during the Indonesian regime. It has a small area (3536 m^2), with few small-sized ponds totalling 1800 m^2 of water surface area. The hatchery used to produce <15,000 mixed-sex tilapia and common carp fingerlings annually until 2014. The project provided funding support for renovation and repair of breeding ponds and hapas and for construction of a compact monosex tilapia hatchery. The hatchery is now serving as the main breeding and quality germplasm multiplication centre by producing broodstock with high genetic quality following the rotational breeding of GIFT cohorts (Abella et al., 1990; Brummett and Ponzoni, 2009). It supplies GIFT brood fry to PPP model hatcheries across the country and also produces monosex fingerlings for distribution to small-scale grow-out farmers.It also provides technical assistance for producing MT hormone-treated feed for other hatcheries involved in the production of all-male sex-reversed tilapia (SRT). This hatchery is also serving as a 'Centre' for practical training on tilapia hatchery and nursery technologies and thus running as a model hatchery by improving its efficiency and scale of operation.

2.3.2. PPP model hatchery 1: Leohito, Bobonaro

This hatchery, registered as MoreDoc Unipessoal Lda, is located near the border with Indonesia, about 125 km west of Dili (Fig. 2). The hatchery is owned by a pioneer fish farmer of the area, with eight working-age members in family with a wide range of skills. The farm has nine ponds with good source of water supply from spring nearby and good access to electricity supply. Water is sourced from a local drinking water supply system, which is approximately 20 m higher in elevation than the pond area, allowing for gravity flow to the hatchery site to fill or top up the tanks and ponds as needed. Construction of the hatchery was completed with family labour and a limited number of hired construction workers with the technical guidance and partial financial support for building materials from the project.

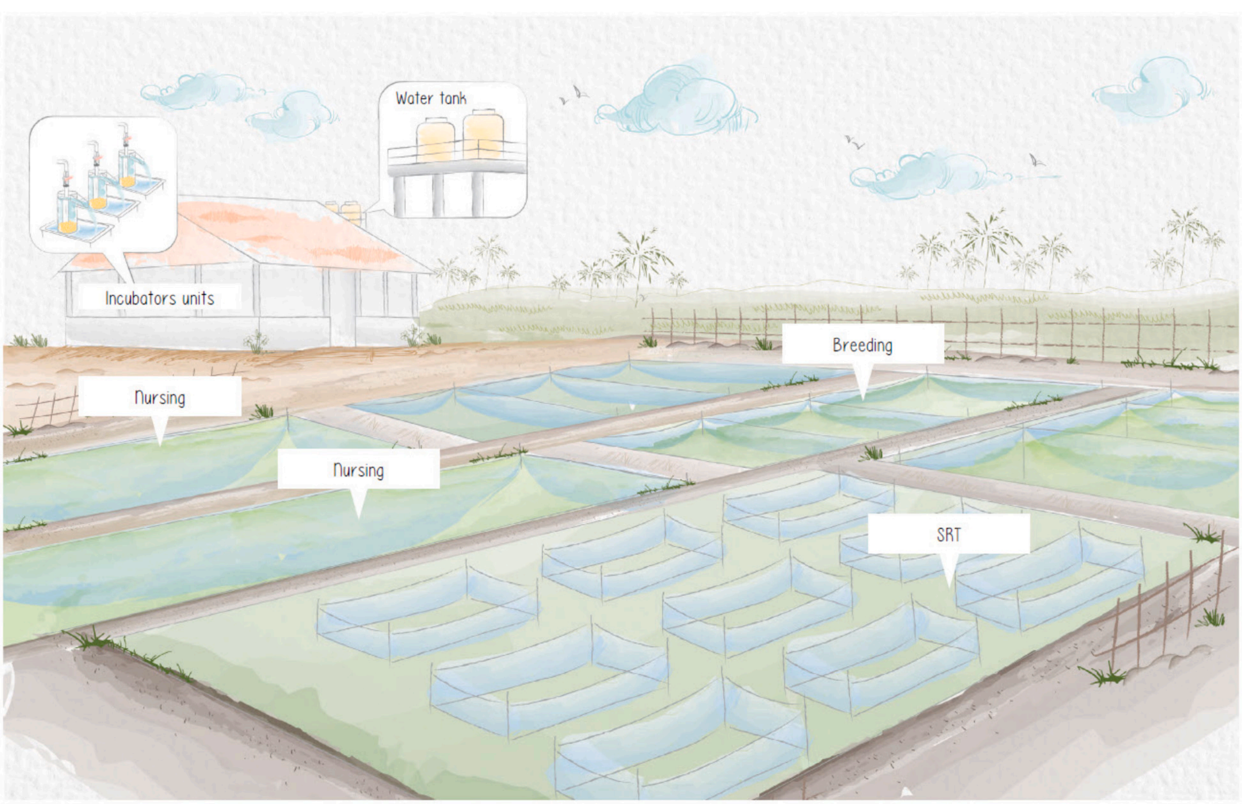

Fig. 3. Schematic diagram of a typical PPP model GIFT hatchery in Timor-Leste (Source: Pant et al., 2020b).

2.3.3. PPP model hatchery 2: Parlamento, Los Palos, Lautem

The hatchery is registered as BlackBird Unipessoal Lda, is located in the eastern part of the country, around 200 km east from Dili (Fig. 2). The hatchery is on sloping land with an excellent water source that allows water to flow from the top to the tanks at the lower elevation. The farmer had already constructed concrete ponds to grow different types of fish in the past. They converted those ponds for the hatchery with the partial funding and technical support by the project. Feasibility study was done in early 2020, just before COVID-19, and design and construction of the hatchery units (incubation and filtration systems, header tank, etc.) were completed with the technical support provided remotely by the project experts and staff during the COVID-19 lockdowns.

2.3.4. PPP model hatcheries 3 and 4: Hera, Dili and Colocau, Manufahi

These hatcheries are located at Shalom Farm in Hera, an outskirt of Dili, and at Colocau in Manufahi in the south of the country (Fig. 2). These were selected from among eight potential sites. Initial site selection started in early 2022, an agreement with Shalom Farm was signed in July and construction completed in December, and the hatchery started producing monosex fry from January 2023. The Colocau hatchery, on the other hand, was a few months behind for its construction but started producing monosex fry from March 2023. Both hatcheries have similar designs and specifications and production and supply capacities to that of the first two PPP model hatcheries. The only difference is that the Hera hatchery uses smaller size concrete tanks for breeding and nursing fry whereas Colocau has larger sized earthen ponds.

2.3.5. Hatchery performance indicators

All the hatcheries collected seed (i.e., eggs, yolk-sac fry or swim-up fry) once weekly from the mouth of incubating females. The following indicators were used to compare the performance of the hatcheries.

Number of seed produced: The number of females having eggs in their mouth and number of seed per spawning female (i.e., clutch) were counted at each harvest. After each harvest, all the eggs and fry were washed with tap water mixed with acriflavine and then weighed by stage (i.e., eggs, yolk-sac fry, and swim-up fry) using a digital balance. The number of seed produced was estimated by counting and weighing the randomly collected 200 seed. Total seed number was estimated by dividing the total weight of seed per harvest by the average weight of sampled seed for their respective stages.

Number of incubated yolk-sac fry: All the unhatched eggs and yolk sac-fry were incubated in cylindrical jars supplied with down-welling water filtered through slow sand and gravel filters. The number of incubated yolk-sac fry was estimated with representative samples and transferred into shallow trays.

Incubation survival (%): It was estimated as the percentage of yolk-sac fry produced or survived out of the eggs incubated in hatching jars.

Number of swim-up fry: It was estimated as the number of swim-up fry produced by each hatchery per month after rearing spawn in trays for about a week.

Number of monosex fry produced: Since male tilapias grow about 50% faster than females, farmers prefer males over females. Hence, male conversion rate (number and %) is considered as a good indicator of seed quality. The swim-up fry were reared for a week in trays before transferring them into hapas for sex-reversal. The swim-up fry in hapas installed in ponds/tanks were fed five times a day for 21 days with the feed mixed with 17-α methyl testosterone hormone (SRT feed) to convert them to male (i.e., monosex) using the standard method as described in Bhujel (2014; Pant et al., 2020b). Monosex fry were raised further for about 2 months and tested using the standard method of gonad squash and the microscopic examination. Percentages of male fry produced by each hatchery were estimated as the indicator of quality (Bhujel, 2014; Pant et al., 2020b).

Statistical analysis: Seed production data for the three hatcheries are shown from the start of their operation (Figs. 4–6). However, since the Parlamento hatchery started producing seed from August 2020 only, seed production data from August 2020 to April 2023 were used for statistical analysis to compare the three hatcheries.

2.3.6. Economic analysis

Economic analysis of the three hatcheries was conducted using capital (fixed) and variable costs. Capital costs included the costs or prices of the following: labour used for land preparation for hatchery and pond construction, construction materials, overhead tank and water pumps, hapas for broodfish, nursery and SRT, incubation jars, larval rearing trays, SRT feed making machine, electricity connection, and refrigerators. Variable costs included the prices of the following: permanent personnel to run the hatchery, daily labour, broodfish, feed used for broodfish, nursery and SRT, MT hormone, alcohol, vitamin pre-mix, etc. Revenues were obtained from broodfish, SRT fry, and other sales. Using the costs of inputs and outputs, the net profit, return on investment (RoI) and internal rate of return (IRR) were calculated for each hatchery and compared among them.

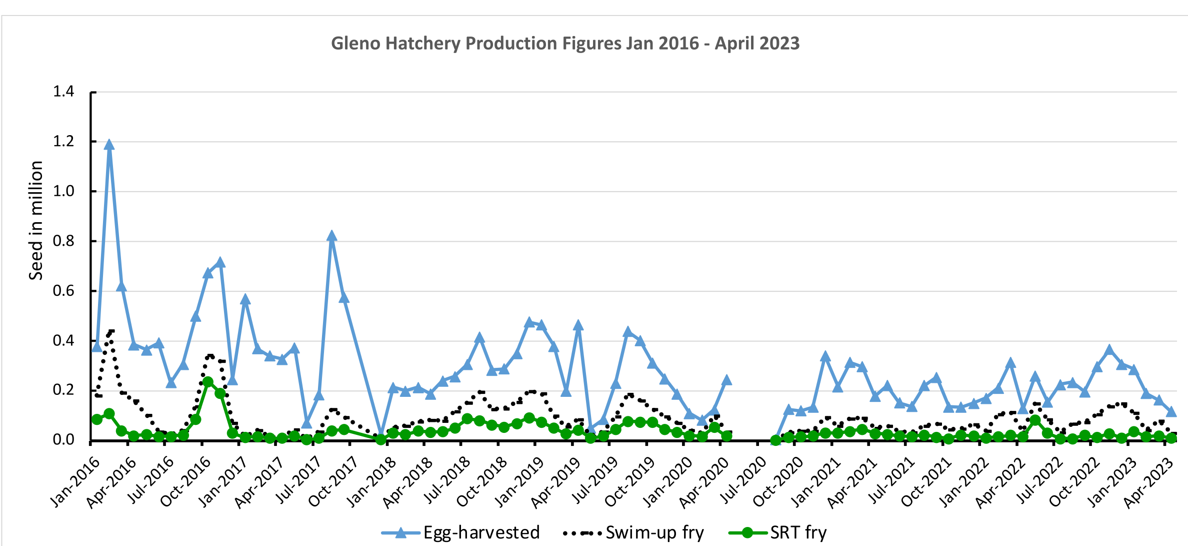

Fig. 4. Seed (egg, swim-up fry and SRT fry) production at the public hatchery, Gleno, Ermera (Hatchery 1) from January 2016 to April 2023.

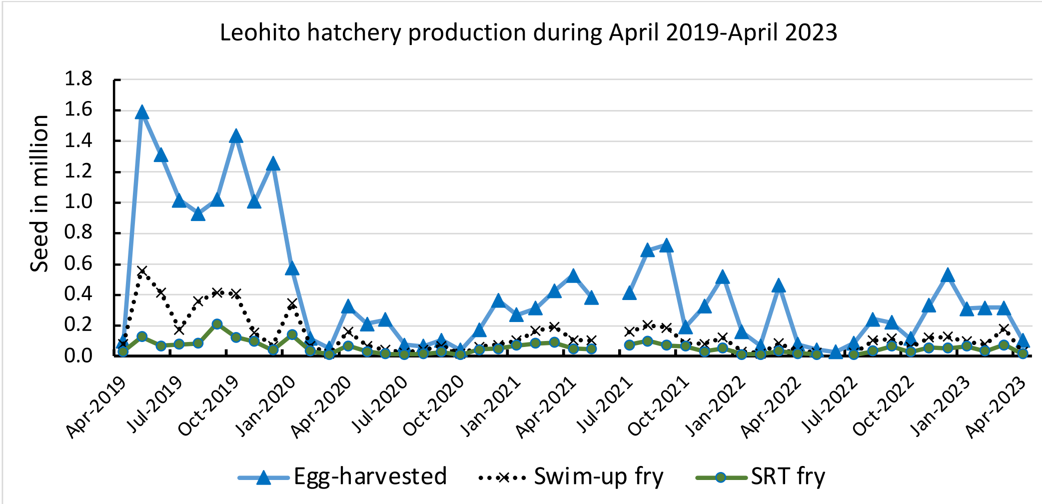

Fig. 5. Seed (egg, swim-up fry and SRT fry) production at the private hatchery, Leohito (Hatchery 2) from April 2019 to April 2023.

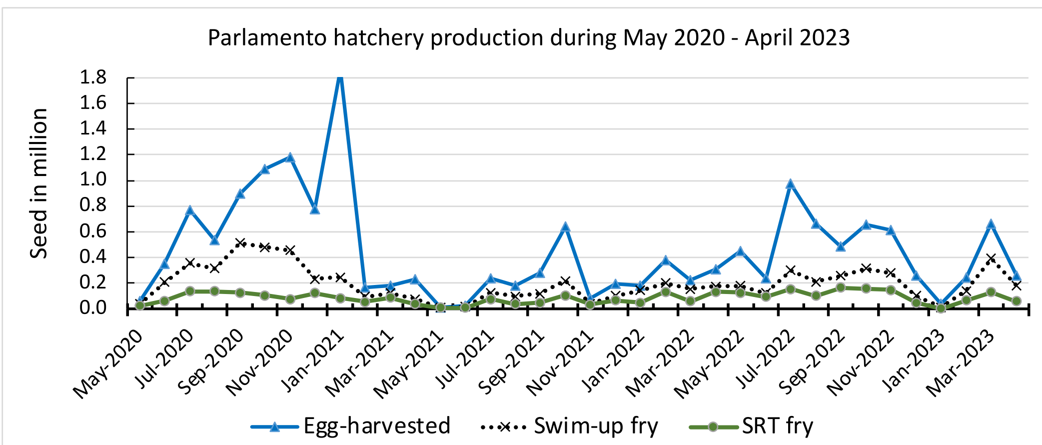

Fig. 6. Seed (egg, swim-up fry and SRT fry) production at the private hatchery, Parlamento (Hatchery 3) from May 2020 to April 2023.

3. Results and discussion

Since data processing and analysis of the recently established two hatcheries is still going on, we present here results from one public hatchery (Gleno) and the first two private hatcheries (Leohito and Parlamento) only.

3.1. Seed production and dissemination by hatcheries

The public hatchery in Gleno started producing seed from January 2016 (Fig. 4), first private hatchery in Leohito from April 2019 (Fig. 5), and the second private hatchery in Parlamento from May 2020 (Fig. 6). Seed production data by these hatcheries for until April 2023 are also summarized in Table 2. However, since complete set of data from the three hatcheries were available only for August 2020 to April 2023, these data were used for statistical analysis (Table 3). Overall, seed production by all hatcheries in the initial years was much higher compared to later years. The Figs. 4 and 5 indicated that production of seed was disrupted during May – July 2020 in Gleno and in 2021 in Leohito due to time taken for changing old broods by new batches which was also done along with pond preparation. Later, these hatcheries changed broods only partially at a time so that they could continue seed

Table 2
Total seed (eggs, swim-up fry and monosex fry) production and monthly average by the three hatcheries as of April 2023 since their establishment.

Parameters		Gleno[1]	Leohito[2]	Parlamento[3]	Total
Seed harvested	Total	23,928,324	20,217,006	16,395,085	60,540,416
	Monthly avg	288,293	421,188	455,419	1,164,900
	St deviation	184,723	400,710	392,293	
Swim-up fry	Total	7,666,565	6,259,941	7,001,625	20,928,131
	Monthly avg	92,368	133,190	194,490	420,048
	St deviation	74,659	123,444	130,929	
Monosex fry	Total	3,137,273	2,600,987	3,019,459	8,757,719
	Monthly avg	37,798	55,340	83,874	177,012
	St deviation	37,356	40,270	46,416	

Notes: Production period: [1]1/2016–4/2023, [2]4/2019–4/2023 [3]5/2020–4/2023.

Table 3
Seed production, clutch, hatching and larval survival of the three hatcheries from August 2020 to April 2023 for statistical comparison [monthly averages ± Standard Error (SE)].

Performance indicators		Gleno	Leohito	Parlamento	Overall
Seed harvested (no.)	Average	205,266^{b}	279,588^{b}	461,144^{a}	315,332
	SE	14,021	33,602	69,630	75,997
Swim-up fry (no.)	Average	69,710^{b}	93,427^{b}	193,993^{a}	119,043
	SE	6436	9898	22,792	38,095
Monosex fry (no.)	Average	22,053^{c}	45,781^{b}	84,797^{a}	50,877
	SE	2588	4616	8052	18,291
Clutch size (seed/spawn)	Average	772^{b}	582^{c}	1172^{a}	842
	SE	24	33	74	174
Incubation survival (%)	Average	33.3^{b}	36.4^{b}	49.4^{a}	39.7
	SE	1.7	2.4	2.7	4.9
Swim-up fry survival (%)	Average	65.3^{a}	48.9^{b}	50.5^{b}	54.9
	SE	2.4	2.1	3.4	5.2

Note: Values with different superscripts are significantly different at 0.05.

production without interruption. In Gleno, production was highest in the initial two years while it was lowest in the recent three years (Fig. 4). For the two PPP model hatcheries, the production was much higher in the first year compared to other years (Fig. 5–6). The low production in the last three years was due to the incidence of COVID-19 that affected aquaculture and fishery sector in Timor-Leste as it did in rest of the world. COVID19-related lockdowns restricted the transportation or movement of inputs (e.g., feed) and outputs, lowered the demand for fingerlings and food fish, and negatively affected the overall agri-food systems (FAO, 2020). It is however interesting to note that the seed production continued at a higher pace in Parlamento even during COVID-19, showing resilience of this site. Results demonstrate that above eight million monosex tilapia fry were produced by April 2023 by the three hatcheries, with monthly average production in Parlamento significantly higher (83,874) than either in Gleno (37,798) or Leohito (55,340) (Table 2). This means that, on an average, over 177,000 monosex fry per month were produced by the three hatcheries, with a capacity of producing about 2 million monosex GIFT fry annually. The Gleno hatchery disseminated SRT fingerlings to 2939 farmers across the country for stocking in 53 ha pond area. Likewise, the two PPP model hatcheries disseminated SRT fingerlings to 829 and 287 farmers respectively.

3.2. Clutches, hatching, and larval survival

Time (month) as a block did not significantly affect the number of seed harvested, swim-up fry and monosex fry produced and clutches, hatching percentage, and larval survival, and did not differ among the hatcheries (Table 3). Comparison of the hatcheries during August 2020 – April 2023 revealed that the number of seed harvested and swim-up fry and monosex fry produced were significantly ($P < 0.05$) higher in Parlamento compared to Gleno or Leohito (Table 2). Since the hatchery in Parlamento was the newest among three hatcheries, it had new broodfish which produced more eggs per spawning. In addition, this hatchery also had higher incubation survival than the other two hatcheries. However, the survival during incubation was <50% which is relatively low compared to the survival in general (Bhujel, 2014). The new working team and better water source and incubation system might have contributed to producing more eggs and fry. The average clutch size of the broods in Parlamento was higher than the ones obtained in earlier studies from a commercial hatchery in Thailand (Bhujel et al., 2000, 2007). The survival of swim-up fry in trays was however higher in Gleno than in the other two hatcheries. Although all three hatcheries were performing quite satisfactorily, results also indicated that all the hatcheries were in need of fine tuning their operation to maximize their efficiency and productivity. Water quality parameters (e.g., water temperature, DO, pH, etc.) may affect hatchery productivity (Bhujel, 2000; Bhujel et al., 2001a&b).

3.3. Sex-reversal

Results of the quality test (Table 4) showed that Parlamento (98 ± 0.2%) had significantly higher quality, i.e., % male, than the fry produced by Leohito (96.5 ± 0.3%). However, differences between Gleno and Parlamento, as well as Gleno and Leohito, were not significant due to high variation in male percentage at the Gleno hatchery. Both Parlamento and Leohito consistently maintained male percentages above the reasonably acceptable level (>95%) and met the requirements of Timor-Leste's infant tilapia industry. However, there is room for improvement to achieve higher quality (>99%), as observed in mature and competitive industries in Bangladesh, Thailand, and elsewhere. Furthermore, optimizing conversion efficiency is necessary to alleviate environmental concerns regarding potential female fish escaping from farmers' ponds. While farmers typically follow proper management systems to prevent escapes, experiences from other countries suggest that critical problems from a few female escapees are unlikely, as they are not carnivorous and their eggs can be consumed by other fish in nature.

3.4. Economic analysis of hatchery business

Table 5 shows the list of major costs, revenue generated, and profits obtained by the hatcheries. As a government hatchery, Gleno distributed the fish seed free to the farmers. Therefore, the revenue for Gleno was estimated assuming seeds were sold at a subsidized price (US$0.03/fry).

Data showed that, on an average, approx. US$31,603 would be required to establish a hatchery and US$12,915 per year as the operational cost. The cost of hatchery building construction was shared between the project and the respective hatchery owners. The total capital investment (cost of building, equipment, machines etc.) and revenues were divided by the no. of years they were in operation as the variable costs (salaries of staff, feed, etc.) were recorded on annual basis. Annual gross profit (revenue – variable cost) was negative only for Government hatchery (Gleno) as the fry price was considered subsidized at US$0.03/fry whereas in case of private hatcheries price was US$0.05/fry. As a result, gross or net profits, ROI, and IRR were all negative, indicating that supplying seed at a subsidized rate can be questionable if a government hatchery wants to be financially viable. As opposed to the government hatchery, both PPP model hatcheries have positive ROIs of 28% and 5%, respectively, indicating that the PPP model hatcheries are more efficient, financially viable, and sustainable. Partial financial support (50%) provided by the project has been the incentive to start up the business. The Leohito hatchery, which has been operating since 2019, was already generating a net profit even when considering the capital investment (including costs of hatchery building construction, equipment, and materials) as expenses. This suggests that fully developed PPP model hatcheries could recover their development costs and begin generating a net profit in approximately 5 years.

For running the nurseries, approx. US$922 capital expense plus almost the same amount (i.e., US$ 914) as operational expense would be

Table 4
Quality test results (% male) of SRT fry by hatchery.

Hatcheries	Sex	Test1	Test2	Test3	Average	SE
Gleno	Males	100	134	107		
	Females	0	15	13		
	Total number	100	149	120		
	% male	**100.0**	**89.9**	**89.2**	**93.0 ^{ab}**	**6.0**
Leo Hito	Males	78	150	106		
	Females	3	5	4		
	Total number	81	155	110		
	% male	**96.3**	**96.8**	**96.4**	**96.5 ^{b}**	**0.3**
Parlamento	Males	161	187	–		
	Females	3	4	–		
	Total number	164	191	–		
	% male	**98.2**	**97.9**	**–**	**98.0^{a}**	**0.2**

Table 5
Economic analysis of three hatcheries run as a business in Timor-Leste (unit rates and totals are in US$).

		Gleno			Leohito			Parlamento		
	Description	Units	Unit rate	Total	Units	Unit rate	Total	Units	Unit rate	Total
A:	**Cost items**									
	I. Capital costs									
	1. Land preparation	1	500	500	1	500	500	1	500	500
	2. Hatchery building	1	12,000	12,000	1	20,000	20,000	1	20,000	20,000
	3. Overhead tank	2	600	1200	2	180	360	1	480	480
	4. Water pump	2	400	800	1	400	400	1	400	400
	5. Aerator pump	1	335	335	1	335	335	1	335	335
	6. Pond construction	12	1200	14,400	1	2200	2200	1	2200	2200
	7. Hapa (all types)	1	2455	2455	1	2455	2455	1	2455	2455
	8. Incubation jars	24	28	672	24	28	672	24	28	672
	9. Larval rearing trays	24	13	312	24	13	312	24	13	312
	10. SRT Feed machine	2	420	840	1	420	420	1	420	420
	11. Electricity	1	150	150	1	300	300	1	300	300
	12. Refrigerator	1	420	420	1	180	180	1	180	180
	13. Hapa washer	1	420	420	1	420	420	1	100	100
	14. Other costs	1	500	500	1	1924	1924	1	1924	1924
	Sub-total (X)			35,004			30,478			30,278
	Cost per annum			2334			2032			2019
	II. Variable costs									
	a. Personnel costs									
	1. Manager	12	225	2700	12	50	600	12	50	600
	2. Position1	12	115	1380	12	50	600	12	50	600
	3. Position2	12	115	1380	12	50	600	12	25	300
	4. Position3	12	115	1380	12	50	600	12	25	300
	5. Position4	12	115	1380						
	b. Broodfish	10,000	0.05	500	10,000	0.05	500	6000	0.05	300
	c. Feeds									
	1. Feed for broods	120	42	5040	120	42	5040	96	42	4032
	2. Feed for nursery	6	42	252	24	42	1008	24	42	1008
	3. Fish meal for SRT Feed	6	42	252	24	42	1008	24	42	1008
	d. MT hormone	2	100	200	2	100	200	2	100	200
	e. Alcohol	120	15	1800	120	15	1800	120	15	1800
	f. Vitamin	6	6	36	6	6	36	6	6	36
	g. Others	2	45	90	2	45	90	2	45	90
	Sub-total (Y)			16,390			12,082			10,274
B:	**Revenues**									
	1. a. Monosex fry sales-1	1,984,148	0.03	59,524	1,046,508	0.05	52,325	292,396	0.05	14,620
	b. Monosex fry sales-2				193,051	0.03	5792	291,214	0.03	8736
	c. Monosex fry sales-3				38,000	0.01	380	4000	0.01	40
	2. Broodfish sales	4200	4	14,700	1050	5	5250	2100	3.5	7350
	3. Other revenues				6	1000	6000	2000	3.5	7000
	Sub-total (Y)			74,224			69,747			37,746
	Revenue/annum			11,419			15,499			10,785
C:	**Gross profit**			(4971)			3417			511
	Net profit			(7304)			1385			(1508)
	Return on Investment			(30.3%)			28.3%			5.0%
	IRR			(4.7%)			4.4%			0.8%

required by each nursery operator (Table 6). As in the hatchery business, since the capital cost was covered by the project, gross margin was considered their net profit. Average net profit of the nursing farmers was US$188 for the nursing period of 1–2 months, or about 34% ROI. It showed that the nursing of fry to fingerlings as a business was financially viable and would justify its promotion.

3.5. Enabling conditions and factors for effective PPP

The complementary roles of the government hatchery and the first PPP model hatchery marked the beginning of developing a network of hatcheries and nurseries that has constituted an effective and reliable seed production and distribution system to support a sustainable aquaculture industry for Timor-Leste. Now the first two PPP model hatcheries have already been playing an important role in dissemination of monosex fingerlings across Timor-Leste. With the start of operation of two new PPP model hatcheries from early 2023, production and dissemination of SRT fingerlings has been increasing. However, for the effective implementation of the PPP model, training and capacity building at various levels, and effective policy and institutional environments and

Table 6
Economics of five fry nursing operators running as a business in Timor-Leste.

Items	Nursery 1	Nursery 2	Nursery 3	Nursery 4	Nursery 5	Average	SE
Costs							
Capital	1050	840	970	500	1250	922	125
Variable	1167	1140	1087	750	425	914	143
Revenues	1270	1220	1220	800	1000	1102	89
Gross margin	103	80	133	50	575	188	98

(All figures are in US$).

effective governance mechanisms are necessary.

3.5.1. Training and capacity building of government and hatchery staff

Maintaining the purity of the brood stock is quite important to produce quality seed of monosex tilapia. Broodfish should be maintained in a controlled environment (in tanks or hapas) so that they will not crossbreed with wild fish. As large size broodfish are difficult to handle during egg collection, they need to be completely replaced by new ones every two years or when they are over 500 g following the all-in all-out system. The retired broodfish can be adequately fed for about a month for fattening, then sold as table fish to generate additional income. The new brood fry batch should be stocked in clean hapas installed in well-prepared ponds. Hence, the project has been providing continuous technical support services and new and refresher training on broodfish management, installation and maintenance of equipment and data recording, and on best management practices associated with hatchery operations and brood stock maintenance to government and hatcheries staff. While capacity building of hatchery staff is important for operation and maintenance of the hatchery, capacity building of government staff is equally important to develop effective leadership skills for forging functioning partnerships between government, non-government, private sector, and national and international research institutions.

The capacity building activities for staff of public and private hatcheries, MAF, and WorldFish included formal trainings at AIT, Thailand and in Timor-Leste. The in-country formal trainings included hands-on training conducted by international experts on aquaculture, although on-site/on-the-job informal trainings or mentoring were organized several times each year. The first international training was conducted in 2014 for two staff followed by four each in 2016 and 2019 and 13 in 2023 (Table 7).

Due to mentoring and training of MAF staff both at central and local levels, there has been a notable improvement in their knowledge and skill in hatchery operation and management. As a result, there have been regular updates of hatchery database by MAF and hatchery staff with a minimal support by international experts and active participation of MAF staff as co-facilitators in the Farmer Field School (FFS) trainings. In addition, the national aquaculture forum organized by MAF and WorldFish is a key means to disseminate results, and also to enhance cooperation and partnership among various stakeholders. Such a forum was initially aimed to be organised bi-annually, but due to COVID-19 pandemic and other unforeseeable reasons, so far three forums have been organized, one each in 2016, 2019 and 2023. These partnership efforts have enabled the full spectrum of aquaculture stakeholders to work in a complementary and coordinated way to achieve the NADS production and consumption targets.

Table 7
Types and dates of national and international trainings and number of persons trained in Thailand and Timor-Leste.

Date/year	Training program	Location	No. of persons	Organization
I: International training				
Jan 13–25, 2014	Tilapia training	AIT, Thailand	2	Gleno hatchery
Sep 19–30, 2016	Study tour	Central, Thailand	2	MAF
Sep 19–20, 2016	Tilapia training	AIT, Thailand	2	Gleno hatchery
Feb 18–28, 2019	Tilapia training	AIT, Thailand	1	WorldFish
			2	Gleno hatchery
			1	Leohito hatchery
October 9–20, 2023	Hatchery training	AIT, Thailand and Nam Sai Farm, Prachinburi Thailand	13	All hatcheries, MAF, WorldFish
	Total		23	
II. Training in Timor- Leste				
June 10–15, 2022	Hatchery training	Timor-Leste	3	MAF
			10	2 each from Gleno, Leohito, Parlamento, Hera, & Colocau
	Nursing LSP & Marketing,	Timor-Leste	15	Private sector
Nov 7–15, 2022	Hatchery training	Timor-Leste	3	MAF
			10	2 each from Gleno, Leohito, Parlamento, Hera, & Colocau
	Total		41	

3.5.2. Training and support services to nursery operators and grow-out farmers

Developing a decentralized seed production and dissemination system is crucial for scaling of aquaculture. Seeing the opportunity to collaborate with the private hatcheries, local farmers have been establishing nurseries in ponds constructed in their homesteads and farmlands and approaching the government through the project to seek initial financial support for establishment of their nursery business. Thus, six nurseries were initially established in western and eastern parts of the country: four in Bobonaro (2 each in Balibo and Batugade) and two in Baucau between August 2019 and February 2020. Currently, nursery operators in Bobonaro are procuring SRT fry from the hatchery in Leohito and those in Baucau from Parlamento. The nursery operators nurse the fry for 4–6 weeks and then sell the fingerlings to local fish farmers for farming in their own ponds. The project has so far provided different types of training on nursing GIFT fingerlings in hapas to over 10 nursery operators. It is anticipated that with the establishment and operation of two new hatcheries and with further increase in number of private hatcheries in the future, there will be greater numbers of nursery operators spread all over the country. Likewise, the FFSs in all municipalities have been providing informal, practical training on best management practices for tilapia production to large number of grow-out farmers.

3.5.3. Effective policies, institutions, and governance

Enabling policies must be put in place to facilitate finance and PPP to support progress towards the NADS target and realize the full potential of aquaculture in Timor-Leste. Murekezi et al. (2018) listed the following key learning from the agribusiness PPP case studies: (i) PPPs should focus on shared interests and it is important that the successful partnerships require a sincere belief that the shared initiative is mutually beneficial, (ii) PPPs require clear identification of roles and responsibilities of each partner for them to be successful, (iii) Implementation of PPPs requires enough time to increase their likelihood of success, (iv) PPP stakeholders should know their markets and set realistic targets, (v) PPP projects can be negatively affected by circumstances beyond their control. These lessons need to be considered while implementing the PPP model to be successful in Timor-Leste and elsewhere.

Likewise, enabling environments and good governance are essential requirements for the PPP projects to be sustainable. There are also other aspects such as policies, institutional capacities and services relating to food safety regulations, establishment and enforcement of standards, contract negotiations and compliance, and market information and rural transport systems that are particularly important for agribusiness and agro industries including aquaculture (Pant et al., 2023a, 2023b).

4. Challenges and opportunities

The PPP model of hatchery establishment and dissemination of quality broodstock and fry by public and private hatcheries and through nursery operators or LSPs to integrate tilapia culture in existing farming systems (holistic approach) is generally functioning well. All the actors of the value chain should be capable of continuing to carry on their duties and responsibilities even when project ceased to support. Required facilities have been built in each hatchery and they have potential to operate at full capacity. However, despite high demand for seed across the country, they tend to be slow in upscaling their operations as they encountered technical and management issues from time to time, necessitating continuous technical support throughout few initial years. The project has been implemented in collaboration with the government. Planning is underway for the gradual transition of support, monitoring, and control responsibilities from the project team to the relevant government entities. This shift aims to ensure the sustainability of current achievements and foster further development.

The following are the challenges critical during their implementation and could become more significant if the project support ends without proper transitioning:

1. Hatchery operators face difficulties in acquiring inputs (fishmeal, hormone, vitamins etc. for feed to produce monosex fry), materials (e.g., jars, trays, hapa nets, graders, etc.), and equipment (e.g. water pumps, aerators), which are mostly imported from abroad and are quite costly.
2. Hiring skilled staff for the PPP model hatcheries has always been a challenge. However, there were several aquaculture graduates from the Universidade Oriental Timor Lorosa'e (UNITAL) who worked as interns in these hatcheries; some of them have been hired by the PPP hatcheries to bridge the staffing gap.
3. Transport of inputs (mainly feed), materials, and equipment from Dili to hatcheries and of fingerlings from hatcheries to nurseries and farmers' clusters has yet to be smooth and timely. The project is partially subsidizing the transportation cost and the LSPs are taking up the responsibilities gradually.
4. During COVID-19, all hatcheries faced numerous challenges due to restrictions on people's movement and the transportation of materials and goods. However, they were able to sustain their operations, albeit at a minimal level, as agricultural activities, including fish farming, were considered essential services. Parlamento hatchery was established during COVID-19 lockdowns with remote technical support.
5. The PPP model hatcheries need regular monitoring and backstopping so that they do not derail from the processes or procedures and continue producing high quality seed. Regular trainings are being provided to government and hatchery staff so as to sustain the hatchery activities beyond the project period.
6. Most of the monosex fry / fingerlings are being sold to the nurseries and farmers in the PADTL2 project municipalities. The PPP model hatcheries have the capacity to produce more and sell to more farmers to increase revenues, but they still lack skills in operating hatcheries to their full capacity and in marketing and promotional activities. They have been encouraged to create their own brochures, websites, as well as to use social media to promote their activities and products.
7. To promote private sector investment in the tilapia value chain, initial investments will be required to establish basic value chain infrastructure such as ponds, hatcheries, access to commercial fish feeds, and market linkages to urban retailers. Investments of approx. US$ 30,000 capital expense plus US$ 1000/month operational expenses would be required to establish and operate one hatchery business and approx. US$ 900 capital expense plus US$ 900 operational expenses per cycle to establish and operate a nursery business by private sector. For a grow-out farmer, the main start-up investment would be for pond digging (approx. US$ 500) and purchase of feed and fingerlings (approx. US$ 1000). Traders would also require start-up funds to purchase 1–1.5 t of fish (approx. US$ 4000/week each) (Sendall et al., 2022). Bank loans and financing are available in Timor-Leste to invest in aquaculture if the basic borrowing requirements can be met.

Commercializing the tilapia value chain has potential to create additional employment opportunities for input suppliers and intermediary traders to aggregate fish from small-scale aquaculture farmers and distribute to retailers in urban centres. The LSPs, self-employed youths recruited and trained by the PADTL, have been playing a pivotal role in input supply (seed, feed) and output (fish) marketing. Some of them are also nursing fry to the fingerlings stage and selling them to farmers (Pant et al., 2023a, 2023b). Currently, there are no veterinary services accessible for aquaculture in Timor-Leste. However, the sustainable intensification of aquaculture promoted by PADTL promotes better management practices that are easily implementable by farmers, hatchery operators, and nursery operators (Pant et al., 2023a, 2023b). Once production and trade increase, there will be a need for efficient and cost effetive refrigeration facilities and transportation of live fish in bulk to nearby markets or cities. Iice and insulated boxes will also be necessary to keep fish fresh at production and retail sites where electric refrigerators or cold rooms are not available.

5. Conclusions and recommendations

The establishment and operation of hatcheries, involving both the public and private sectors with their complementary roles, are essential for the development of sustainable aquaculture in small-scale resource-poor farming systems. However, it requires a long-term strategic visionary plan, commitment, and continuous technical, financial, and policy support. Despite facing some challenges that require fine-tuning of the systems to maximize efficiency and productivity, the PPP model hatcheries in Timor-Leste have demonstrated success in operating viably, supplying high-quality monosex GIFT seeds to fish farmers, and playing a pivotal role in the scaling of aquaculture. The PPP model hatcheries are simple and replicable models with the potential to be scaled nationwide. Clearly, the PPP model-based GIFT seed production and dissemination system adopted in Timor-Leste has been a win-win for both public and private sectors as it helps supplying high quality seed to a large number of farmers ensuring the production of fish required for food and nutrition security, create employment opportunities, and run as profitable business. The PPP model hatcheries in Timor-Leste have been the foundation of the success story of aquaculture development and its integration into existing farming systems. This model should also serve as a blueprint for adoption in other countries, particularly in small island developing states (SIDS) facing similar challenges such as food and nutrition insecurity, rapid population growth, high levels of poverty and unemployment, comparable agro-ecological and farming systems, geographical settings, and all impacted by climate change.

CRediT authorship contribution statement

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

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Jharendu Pant reports financial support was provided by WorldFish, Penang, Malaysia. If there are other authors, they 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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References

Abella, T.A., Palada, M.S., Newkirk, G.F., 1990. Within family selection for growth rate with rotation mating in Oreochromis niloticus. In: The Second Asian Fisheries Forum, Hirano, R., Hanyu, I. (Eds.), Asian Fisheries Society. Philippines, Manila, pp. 515–518.

Public and private partnerships in aquaculture: A case study on tilapia research and development. In: Acosta, B.O., Sevilleja, R.C., Gupta, M.V. (Eds.), 2006. WorldFish Center Conf. Proc, 72, 72 p.

ADB (Asian Development Bank), 2005. An Impact Evaluation of the Development of Genetically Improved Farmed tilapia and their Dissemination in Selected Countries. Operations Evaluation Department, Asian Development Bank, Manila, Philippines.

AMSAT International, 2011. Fish and Animal Protein Consumption and Availability in Timor-Leste. Regional Fisheries Livelihoods Programme for South and Southeast Asia (GCP/RAS/237/SPA) Field Project Document 2011/TIM/02.

Andersen, A.B., Pant, J., Thilsted, S.H., 2013. Food and nutrition security in Timor-Leste. In: CGIAR Research Program on Aquatic Agricultural Systems. Penang, Malaysia. Project Report AAS-2013-29. https://hdl.handle.net/20.500.12348/906.

Andrew, N., Kam, S.P., Philips, M., 2011. Mapping fisheries dependence in Timor-Leste: A Scoping Study. Coral Triangle Support Partnership, 21 p. http://www.coraltriangleinitiative.org/sites/default/files/resources/CTSP_ManagingFisheriesDependence_TL_Sept2011.pdf.

Baqui, M.A., Bhujel, R.C., 2011. A hands-on training helped proliferation of tilapia culture in Bangladesh. In: Liping, L., Fitzsimmons, K. (Eds.), Better Science, Better Fish, Better Life, Proceedings of the Ninth International Symposium on Tilapia in Aquaculture. Aqua-Fish Collaborative Research Support Program, pp. 311–322, 409 p.

Barange, M., Bahri, T., Beveridge, M., Cochrane, K., Funge-Smith, S., Poulain, F., 2018. Impacts of climate change on fisheries and aquaculture: Synthesis of current knowledge, adaptation and mitigation options. In: FAO Fisheries and Aquaculture Technical Report #627, 628 p.

Bell, J.D., Johnson, J.E., Hobday, A.J., 2011. Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change. Secretariat of the Pacific Community, Noumea, New Caledonia, 925pp.

Bhujel, R.C., 2000. A review of strategies for the management of Nile tilapia (*Oreochromis niloticus*) broodfish in seed production systems, especially hapa-based systems. Aquaculture 181, 37–59.

Bhujel, R., 2011. How to produce billions of high-quality tilapia fry. In: Liping, L., Fitzsimmons, K. (Eds.), Better Science, Better Fish, Better Life Proceedings of the Ninth International Symposium on Tilapia in Aquaculture. Aqua-Fish Collaborative Research Support Program.

Bhujel, R.C., 2014. A Manual for Tilapia Business Management. CABI Publishing, Wallingford, UK. ISBN (10): 1780641362, 216 p.

Bhujel, R., Suharman, I., 2021. Food and nutrition security in the context of COVID-19 and the potential role of tilapia aquaculture. IOP Conf. Ser. Earth Environ. Sci. 695, 012023 https://doi.org/10.1088/1755-1315/695/1/012023.

Bhujel, R.C., Woollard, M., 2011. Public-Private Partnerships Boost Tilapia Monosex Fry Production. Global Aquaculture Advocate, November/Dec. 2011, pp. 26–27.

Bhujel, R.C., Turner, W.A., Yakupitiyage, A., Little, D.C., 2000. Broodfish selection and its effect on seed output of Nile tilapia (*Oreochromis niloticus*) in large-scale commercial seed production system. In: Fitzsimmons, K., Filho, J.C. (Eds.), Tilapia Aquaculture in the 21st Century - Proceedings of the 5th International Symposium on Tilapia in Aquaculture (ISTA5), Rio de Janeiro-RJ, Brazil, Sep 3-7, 2000, vol. 2, pp. 334–340, 682 p.

Bhujel, R.C., Yakupitiyage, A., Little, D.C., Turner, W.A., 2001a. Selection of a commercial feed for Nile tilapia (*Oreochromis niloticus*) broodfish breeding in a hapa-in-pond system. Aquaculture 194, 303–314.

Bhujel, R.C., Turner, W.A., Yakupitiyage, A., Little, D.C., 2001b. Impacts of environmental manipulation on the reproductive performance of Nile tilapia (*Oreochromis niloticus*). J. Aquac. Tropics 16 (3), 197–209.

Bhujel, R.C., Little, D.C., Hossain, M.A., 2007. Reproductive performance and the growth of stunted and normal Nile tilapia (*Oreochromis niloticus*) broodfish at varying feeding rates. Aquaculture 273, 71–79.

Bjärstig, T., 2017. Does collaboration lead to sustainability? A study of public–private partnerships in the Swedish mountains. Sustainability 9, 1–22.

Brummett, R.E., Ponzoni, R.W., 2009. Concepts, alternatives, and environmental considerations in the development and use of improved strains of Tilapia in African aquaculture. Rev. Fish. Sci. 17 (1), 70–77. https://doi.org/10.1080/10641260802083174.

CWW, Concern Worldwide and Welthungerhilfe, 2022. Global Hunger Index 2022: Timor-Leste. https://www.globalhungerindex.org/pdf/en/2022/Timor-Leste.pdf.

Da Costa, M., Lopes, M., Ximenes, A., Ferreira, A., Spyckerelle, L., Williams, R., Nesbitt, H., Erskine, W., 2012. Household food insecurity in Timor-Leste. Food Secur. 5 https://doi.org/10.1007/s12571-012-0228-6.

Dey, M.M., Rosegrant, Mark W., Gosh, Kamal, Chen, Oai Li, Valmonte-Santos, Rowena, 2016. Analysis of the economic impact of climate change and climate change adaptation strategies for fisheries sector in Pacific coral triangle countries: model, estimation strategy, and baseline results. Mar. Policy 67, 156–163.

DRTL, Democratic Republic of Timor-Leste, 2017. National Food and Nutrition Security Policy. Dili: 765 Democratic Republic of Timor-Leste (DRTL).

Eknath, A.E., Bentsen, H.B., Ponzoni, R.W., Rye, M., Nguyen, N.H., Thodesen, J., Gjerde, B., 2007. Genetic improvement of farmed tilapias: composition and genetic parameters of a synthetic base population of *Oreochromis niloticus* for selective breeding. Aquaculture 273, 1–14.

El-Sayed, A.F., 2006. Tilapia Culture. CAB International, 277 p.

FAO (2016a). Sustainable Intensification of Aquaculture in the Asia-Pacific Region. Documentation of Successful Practices. Miao, W. and Lal, K.K. (Ed.), Bangkok, Thailand.

FAO (2016b). Public–Private Partnerships for Agribusiness Development – A Review of International Experiences, Rankin, M., Gálvez Nogales, E., Santacoloma, P., Mhlanga, N. & Rizzo, C. Rome, Italy.

FAO, 2020. National Agrifood Systems and COVID-19 in Timor-Leste Effects, Policy Responses, and Long-Term Implications, Rome. https://www.fao.org/3/cb1341en/CB1341EN.pdf.

FAO, 2022. The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation. Rome, FAO. https://doi.org/10.4060/cc0461en.

Georgeou, N., Hawksley, C., Wali, N., Lountain, S., Rowe, E., West, C., et al., 2022. Food security and small holder farming in Pacific Island countries and territories: a scoping review. PLOS Sustain. Transform. 1 (4), e0000009 https://doi.org/10.1371/journal.pstr.0000009.

ICLARM/UNDP (International Centre for Living Aquatic Resources Management/ United Nations Development Programme), 1998. Estimated heritability within each environment, and across all environments, during each generation. In: Genetic Improvement of Farmed Tilapias (GIFT) Final Report, Part 2, Attachment 6. United Nations Development Programme and WorldFish Centre, Penang, Malaysia.

Little, D.C., Hulata, G., 2000. Strategies for tilapia seed production. In: Meveridge, M.C.M., McAnrew, B. (Eds.), Tilapia Biology and Exploitation, Springer. Fish and Fisheries Series, vol. 25. Springer, Dordrecht, pp. 267–326. https://doi.org/10.1007/978-94-011-4008-9_8.

Little, D.C., Turner, W.A., Bhujel, R.C., 1997. Commercialization of a hatchery process to produce MT-treated Nile tilapia in Thailand. p. 108-118. In: Alston, D.E., Green, B. W., Clifford, H.C. (Eds.), IV Symposium on Aquaculture in Central America: Focusing on Shrimp and tilapia, 22–24 April 1997. Asociacion Nacional de Acucultores de Honduras and the Latin American Chapter of WAS, Tegucigalpa, Honduras, 237 p.

López-Angarita, J., Hunnam, K.J., Pereira, M., Mills, D.J., Pant, J., Teoh, S.J., Eriksson, H., Amaral, L., Tilley, A., 2019. Fisheries and Aquaculture of Timor-Leste in 2019: Current Knowledge and Opportunities. WorldFish, Penang, Malaysia (Program Report: 2019-15).

Moses, M., Chauka, L.J., de Koning, D.J., Palaiokostas, C., Mtolera, M.S.P., 2021. Growth performance of five different strains of Nile tilapia (*Oreochromis niloticus*) introduced to Tanzania reared in fresh and brackish waters. Sci. Rep. 11, 11147. https://doi.org/10.1038/s41598-021-90505-y.

Murekezi, P., Menezes, A., Ridler, N., 2018. Contract farming and public–private partnerships in aquaculture. Lessons learned from East African countries. In: FAO Fisheries and Aquaculture Technical Paper No. 623. Rome, Italy.

Naylor, R.L., Hardy, R.W., Buschmann, A.H., Bush, S.R., Cao, L., Klinger, D.H., Little, D. C., Lubchenco, J., Shumway, S.E., Troell, M., 2020. A 20-year retrospective review of global aquaculture: review. Nature 591, 551–563.

NDFA/MAF, 2012a. Analyses of the Current Situation and Potential for Aquaculture Development in Timor-Leste. National Directorate of Fisheries and Aquaculture (NDFA), Ministry of Agriculture and Fisheries (MAF), Rua Presidente Nicolau Lobato, N°5, Comoro, Dili, Timor-Leste.

NDFA/MAF, 2012b. National Aquaculture Development Strategy 2012-2030. National Directorate of Fisheries and Aquaculture (NDFA), Ministry of Agriculture and Fisheries (MAF), Rua Presidente Nicolau Lobato, N5, Comoro, Dili, Timor-Leste.

Pant, J., Teoh, S.J., Gomes, S., Pereira, M., Kam, S.P., 2020a. Partnership for Aquaculture Development in Timor-Leste: Looking Back, Looking Forward. WorldFish, Penang, Malaysia (Program Brief: 2020-11).

Pant, J., Teoh, S.J., Gomes, S., Dani, A., De Jesus, L.S., Pereira, M., Bhujel, R.C., 2020b. Better Management Practices for Monosex tilapia Seed Production: An Illustrated Guide. WorldFish, Penang, Malaysia (Booklet: 2020-12).

Pant, J., Teoh, S.J., Gomes, S., Pereira, A., Pereira, M., de Jesus, L.S., Carmu, A.D., Bhujel, R.C., 2023a. Sustainable intensification of Genetically Improved Farmed

Tilapia (GIFT) in Timor-Leste's farming systems: challenges and opportunities. Agric. Syst. 216, 103874. April 2024.
Pant, J., Gomes, S., Teoh, S.J., Pereira, A., De Jesus, L.S., du Karmu, A.D.F., Pereira, M., Shrestha, M.K., Bhujel, R.C., 2023b. Better Management Practices (BMP) for Grow-out Farming of Genetically Improved Farmed Tilapia (GIFT) in Timor-Leste. WorldFish, Penang, Malaysia. Manual: 2023-52.
Pickering, T.D., Ponia, B., Hair, C.A., Southgate, P.C., Poloczanska, E.S., Della Patrona, L., Teitelbaum, A., Mohan, C.V., Phillips, M.J., Bell, J.D., De Silva, S., 2011. Vulnerability of aquaculture in the tropical Pacific to climate change. In: Bell, J.D., Johnson, J.E., Hobday, A.J. (Eds.), Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change. Secretariat of the Pacific Community, Noumea, New Caledonia, pp. 647–731.
Ponzoni, R.W., Nguyen, N.H., Khaw, H.L., Hamzah, A., Bakar, K.R.A., Yee, H.Y., 2011. Genetic improvement of Nile tilapia (*Oreochromis niloticus*) with special reference to the work conducted by the WorldFish center with the GIFT strain. Rev. Aquac. 3, 27–41. https://doi.org/10.1111/j.1753-5131.2010.01041.x.
Robins, L., Crimp, S., van Wensveen, M., Alders, R.G., Bourke, R.M., Butler, J., Cosijn, M., Davila, F., Lal, A., McCarthy, J.F., McWilliam, A., Palo, A.S.M., Thomson, N., Warr, P., Webb, M., 2020. COVID-19 and Food Systems in the Indo-Pacific: An Assessment of Vulnerabilities, Impacts and Opportunities for Action. ACIAR Technical Report 96, Canberra, 254 pp.
Rosegrant, M., Dey, M., Santos, R.A., Chen, O., 2016. Economic impacts of climate change and climate change adaptation strategies in Vanuatu and Timor-Leste. Mar. Policy 67. https://doi.org/10.1016/j.marpol.2015.12.010.
Sendall, A., Pinto, L.G., Salu, R.C., Gomes, S., Almeida, C.J.A., Teoh, S.J., Pant, J., 2022. Value Chain and Market Analysis of the Aquaculture Sector in Timor-Leste. Partnership for Aquaculture Development in Timor-Leste-2. WorldFish Center, Penang, Malaysia, 38p.
Sinha, V.R.P., Keshavanath, P., Sharma, A.P., Mohanty, B.P., 2016. Public Private Partnerships in Aquaculture. Narendra Publishing House, New Delhi, India.
Steenbergen, D.J., Eriksson, H.B., Hunnam, K., Mills, D.J., Stacey, N., 2019. Following the fish inland: understanding fish distribution networks for rural development and nutrition security. In: Faculty of Law, Humanities and the Arts - Papers. 4054. https://ro.uow.edu.au/lhapapers/4054.
Tran, N., Shikuku, K.M., Rossignoli, C.M., Barman, B.K., Cheong, K.C., Ali, M.S., Benzie, J.A.H., 2021. Growth, yield and profitability of genetically improved farmed tilapia (GIFT) and non-GIFT strains in Bangladesh. Aquaculture 536, 736486. https://doi.org/10.1016/j.aquaculture.2021.736486.
Tveteras, R., Nystoyl, R., Jory, D.E., 2019. Goal 2019. Finfish production review and forecast. Global Seafood Alliance. https://www.globalseafood.org/advocate/goal-2019-global-finfish-production-review-and-forecast/.
Weirowski, F., Hall, S.J., 2008. Public-Private Partnerships for Fisheries and Aquaculture: Getting Started. WorldFish Center Manual Number 1875. The WorldFish Center, Penang, Malaysia.
Weirowski, F., Liee, A., 2010. Public Private Partnerships in Small-Scale Aquaculture and Fi Sheries. Policy Brief No. 2135. The WorldFish Center, Penang, Malaysia, 8 pp.
WFP, 2022. Country Brief - Timor-Leste. World Food Programme. https://reliefweb.int/report/timor-leste/wfp-timor-leste-country-brief-july-2022.
World Bank, 2013. Fish to 2030: Prospects for Fisheries and Aquaculture. World Bank, Washington, p. 102.