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Barriers to tilapia aquaculture in Papua New Guinea, Solomon Islands and Timor-Leste

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Barriers to tilapia aquaculture in Papua New Guinea, Solomon Islands and Timor-Leste

Leo Nankervis, Michael John Phillips, Timothy Pickering, Jesmond Sammut, Joshua Noiney, Jharendu Pant, Daykin Harohau, Chinthaka Hewavitharane, Salote Waqairatu and Geoff Allan

ACIAR

2025

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Cover: National Fisheries Authority's Aquaculture and Inland Fisheries Unit Manager, Jacob Wani, with lead farmer, Jonah, at Sirinumu Reservoir. Cage-based farming at this location has been supported by training.
Photo: Jes Sammut, University of NSW

Dedication – Dr Timothy Pickering

This report is dedicated to one of its authors, Dr Timothy Pickering, who passed away in 2024. Dr Pickering was a staunch advocate for aquaculture in the Pacific and a major contributor to this report. Dr Pickering was an inspirational leader at The Pacific Community (SPC), a champion for aquaculture in Fiji and the Pacific, a highly valued partner to ACIAR and a colleague and great friend to the other authors of this report. He is greatly missed by family, friends and the broad Pacific aquaculture community.

Foreword

The Australian Centre for International Agricultural Research (ACIAR) is mandated to work with partners across the Indo-Pacific region to generate the knowledge and technologies that underpin improvements in agricultural productivity, sustainability and food system resilience. We do this by funding, brokering and managing research partnerships for the benefit of partner countries and Australia.

The development of aquaculture in the Indo-Pacific region is seen as an opportunity to enhance food security and provide livelihood options for rural communities. In parts of Asia and South America, tilapia aquaculture has become a critical source of protein for local populations and has been shown to be an avenue of growth for smallholder enterprises. However, there has been limited growth in tilapia aquaculture in Timor-Leste and Pacific island countries.

For several decades, ACIAR has invested in research focused on technical aspects of tilapia production as well as agribusiness projects which consider the potential of smallholder tilapia aquaculture for development in the Pacific region. The research results suggest that, if production costs can be kept low, there are viable, smallholder inclusive business and investment opportunities for tilapia pond aquaculture in Pacific island countries.

While the literature on tilapia aquaculture is extensive, it does not provide accessible solutions to address the specific challenges of tilapia aquaculture in Timor-Leste and Pacific island countries. To understand and guide future research investment, ACIAR commissioned a review of the major challenges to tilapia aquaculture in Papua New Guinea, Solomon Islands and Timor-Leste.

The results of the review, published in this technical report, provide insight into important areas of focus for future research and capacity development. The report also interprets the information available in the context of contemporary challenges, such as climate change, market-oriented value chains, and social and cultural attitudes towards tilapia and tilapia farming.

This publication is designed to serve as a 'roadmap' for future developmental assistance aimed at improving tilapia aquaculture in Pacific island countries and Timor-Leste.

Prof Wendy J Umberger
Chief Executive Officer, ACIAR

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Acronyms and abbreviations

ACIAR	Australian Centre for International Agricultural Research
ACP	African, Caribbean and Pacific states/countries
BSF	Black soldier fly
BSFL	Black soldier fly larvae
FCR	Food Conversion Ratio
GIFT	Genetically Improved Farmed Tilapia
LSPs	Local service providers
MSME	Micro, small and medium
NGO	Non-government organisation
ODA	Official development assistance
PADTL	Partnership for Aquaculture Development in Timor-Leste project
PIC	Pacific island countries
PNG	Papua New Guinea
SDA	Specific dynamic action
SDGs	Sustainable Development Goals (United Nations)
SIDS	Small island developing states
SME	Small to medium enterprise
SPC	Secretariat of the Pacific Community

ACIAR

ACIAR is established by the *Australian Centre for International Agricultural Research Act 1982* (the ACIAR Act), as amended. ACIAR is part of the Foreign Affairs and Trade portfolio. The CEO of ACIAR reports directly to the Minister for Foreign Affairs.

Also established under the ACIAR Act are two advisory groups. The Commission for International Agricultural Research provides decision-making and expert strategic advice to the Minister for Foreign Affairs on the operations of ACIAR. The Policy Advisory Council reports to the Minister for Foreign Affairs, the Commission for International Agricultural Research and ACIAR on issues, programs and policies affecting agriculture in developing countries.

Executive summary

Growth of tilapia aquaculture has been extremely successful in many countries and global growth has been extraordinary. However, despite compelling reasons why tilapia aquaculture is a good option for Pacific island countries, and has been identified as one solution to the projected shortfall in fish protein supplies, growth has been much slower in the Pacific region than in Asia and South America.

This report provides an update on the current status of tilapia aquaculture and covers the challenges with tilapia aquaculture in Pacific island countries and Timor-Leste, with a focus on Papua New Guinea, Solomon Islands and Timor-Leste. The focus is to identify nutrition bottlenecks in fish production and in the production of quality fingerlings, as well as to develop a deeper understanding of the drivers and barriers to tilapia farming more generally.

The report also examines research needs and technical capacity requirements to provide a foundation for locally based higher-quality research and capacity building that is essential to the sustainable growth of aquaculture in Pacific island countries and Timor-Leste.

Pacific island countries and Timor-Leste are characterised by small populations and therefore trade markets are smaller in scale with lower overall demand for produce. We believe there are 4 categories of challenges that combine to constrain the growth of tilapia aquaculture in this region:

- consistent availability of high-quality, single-sex fingerlings
- availability of cost-effective feeds and feeding solutions
- stimulating and sustaining economically viable enterprises
- ensuring capacity building and training meet the needs of farmers, associated businesses and entrepreneurs, extension officers, policymakers and educators.

Hatchery production of high-quality fingerlings has been solved in most countries where tilapia is grown. However, barriers remain in the Pacific. In some Pacific island countries, while tilapia has been introduced, and some poorly performing stocks are being cultured, improving access of farmers to genetically improved Nile tilapia is urgently needed (for example, Solomon Islands). In Timor-Leste, GIFT (Genetically Improved Farmed Tilapia) has been introduced, with genetic quality maintained through rotational breeding of its cohorts. In many other Pacific island countries, careful management of broodstock to maintain genetic quality is also urgently required.

The small scale of each country, plus issues with importation of essential chemicals for consistent hatchery production of single-sex fingerlings constrains growth. Private investment is also needed for development, including satellite hatcheries, and distribution centres for remote and difficult to access farms.

Cost-effective feeds and feeding solutions are difficult everywhere but the small scale of the industry, the small population and the high cost of imports make this a particular challenge for Pacific island countries. Potential 'solutions' will depend on the type (scale) of tilapia farms. For subsistence and community farms, natural productivity enhanced by fertilisation and supplemented with single ingredients is likely to be the feed pathway. The potential role of insect meal, for example, black soldier fly larvae, possibly in conjunction with duckweed production in grow-out ponds should be explored. For small-scale commercial farms, manufactured pellets, potentially made in-country using at least some local feed ingredients should be explored. There is a strong case for continuing the subsidised import of commercially extruded tilapia feeds. This will fast-track industry development, help identify production capacity of different types of farms, and help the upskilling of tilapia farmers.

Stimulating private enterprise investment, particularly for small- and medium-scale enterprises will be fundamental to ongoing growth of tilapia farming in Pacific island countries. Strong support from government agencies is critical, particularly in the early stages of tilapia production, but a pathway for private investment and sustaining tilapia aquaculture through business, even if on a small scale, is essential. Building the case for investment will require an understanding of the marginalised supply chain issues, the limitations in available markets, the socioeconomic drivers for production, and improved support for early-stage tilapia businesses and entrepreneurs in Pacific island countries.

Perhaps the common feature of all challenges for tilapia aquaculture in Pacific island countries is the need for capacity and training. Capacity building is a broad term encompassing the ability to adapt specialised skills and knowledge to local conditions to enhance development outcomes. Enhancing the knowledge, skills and abilities of entrepreneurs and individuals working in aquaculture, including farmers, managers and employees in associated business, extension officers, policymakers and educators, requires appropriate training, resources and support. For capacity building and to address all the challenges described in this review, there is a role for government support and regional coordination.

About this report

This technical report is the result of a review commissioned by ACIAR to explore and document the barriers to tilapia aquaculture in Papua New Guinea, Solomon Islands and Timor-Leste. Many of the review findings also apply to other Pacific island countries. The review was delivered to ACIAR in October 2023.

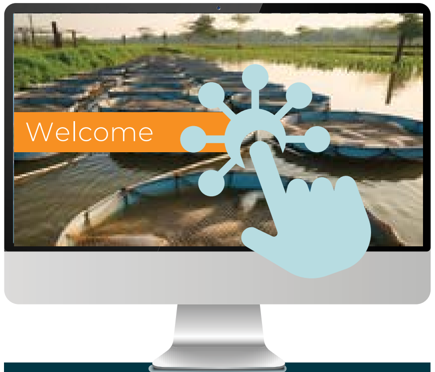
The review was intended to help identify nutrition bottlenecks in fish production and in the production of quality fingerlings, as well as to develop a deeper understanding of the drivers and barriers to tilapia farming more generally. It drew on findings from the desktop review of available literature that examined research needs and technical capacity requirements to provide a foundation for locally based higher-quality research and capacity building that is essential to the sustainable growth of aquaculture in Pacific island countries and Timor-Leste.

A special session on Pacific island aquaculture was organised at *World Aquaculture 2023* in Darwin, which was held from 28 May to 4 June 2023. Experts in the status of aquaculture in Pacific island countries and Timor-Leste were interviewed and invited to give keynote presentations at the Pacific island aquaculture session. The presentations and ensuing discussion shaped the direction of this review (see **Figure 1**).

The recommendations in this report will be useful for those seeking to invest in international development assistance using tilapia aquaculture as a pathway to address food security priorities in the Pacific region. This report will also be a valuable reference for fisheries specialists in the public, private and non-government organisation (NGO) sectors who provide technical advice to farmers, government officials, extension officers and industry network personnel.

Call to action areas

Pacific Island Aquaculture



Policies and regulations

A call to action on driving various unified policies and regulations that support sustainable aquaculture practices and operations and the role of aquaculture in ensuring food security in each Pacific region.

Why we need a Pacific Island sustainable aquaculture info toolbox

+ The importance of collaboration and knowledge sharing among stakeholders in the Pacific Island aquaculture industry.
+ To develop sustainable and integrated aquaculture practices that take into account the unique environmental and cultural contexts of the Pacific Islands.
+ Collaboration and knowledge sharing among stakeholders in the Pacific Island aquaculture industry.
+ The need for capacity building and training programs to support the development of sustainable aquaculture practices in each Pacific region.
+ The use of digital platforms and technology to facilitate development, including knowledge sharing, development of localised SOPs and support training, internships, resources, pilot school / prison programs and digital tools in aquaculture.

Tilapia enterprise in the Pacific top 10 challenges and opportunities:

1. The need to develop local business and technology dissemination centres, sustainable tilapia farming business practices and expansion of satellite hatcheries, that take into account the unique environmental and cultural contexts of the Pacific Islands.
2. The potential for tilapia farming and small-scale feed manufacture to contribute to economic development and food security in the region.
3. The need for capacity building and training programs to support the development of sustainable tilapia farming practices – unique to each region.
4. The importance of developing high-value, nature-friendly and economical feed and products to increase the profitability of tilapia farming.
5. Develop and market strategies to encourage private investment in tilapia farming and marketing.
6. The need for policies and regulations that support sustainable tilapia farming practices and small business support in the Pacific Islands.
7. The importance of empowering local farmers and women to participate in tilapia farming at private and community level.
8. The capacity to form a varied and interconnected network association that harmonises the interests of the public, private sectors, and the government.
9. To focus on scaling tilapia and existing opportunities and successes (rather than too much more R&D on new species).
10. The challenges of addressing the environmental impacts of tilapia farming, such as water pollution and disease outbreaks – region to region.

Public and private partnerships

The need to take a sustainable business approach, and align public support to encouraging tilapia enterprises to grow and sustain. This should also help promote and market sustainable and unique identity driven aquaculture development for each region.

Socio-economic research

The need for socio-economic research to understand the complex relationship between subsistence and commercial aquaculture in the Pacific Islands. Consider looking at existing researchers and scientists out in field and capturing their data and day to day observations – to be plugged into an partnered within and integrated Aquaculture Toolbox.

Figure 1 Call to action areas summarised as key takeaways from the Pacific Island Aquaculture session

Photo: Jes Sammut, University of NSW

The Fish for Prisons program teaches prisoners fish farming skills to help them establish a livelihood on release, PNG.

1 Introduction

Tilapia prepared for cooking, Timor-Leste.

1 Introduction

Fish make up the majority of animal-derived protein for communities living in Pacific island countries, particularly in rural and coastal regions (Bell et al. 2009). This nutrient supply is expected to become increasingly scarce, due to a combination of overfishing and climate change (Friedlander and Gaymer 2021), exacerbating Pacific island malnutrition issues, particularly juvenile stunting and adult obesity (Hiruy and Eversole 2020; Bogard et al. 2021). At the same time, highly processed food is becoming more economically available, shifting the landscape of nutrient supply for Pacific island residents (Sievert et al. 2019). Inland communities have particularly limited access to protein and have particularly homogenous diets (Hiruy and Eversole 2020). In addition to protein, fish supply essential fatty acids, vitamins and minerals that are critical for health and development (O'Meara et al. 2023). An economically viable supply of fish protein has a high potential to alleviate malnutrition through the supply of protein and other essential nutrients and adding nutritional diversity critical for normal development and health (Golden et al. 2021; Byrd et al. 2022).

Fish production at a low trophic niche, with low-cost inputs and achievable technical demands therefore plays a critical role in food security and nutritional health of isolated and poor inland communities.

Tilapia uniquely meets these criteria for tropical fish production. Papua New Guinea (PNG), Solomon Islands and Timor-Leste are linked by their nature of isolated tropical island communities with established tilapia production facilities, but still have significant challenges in malnutrition (United Nations n.d.). This review examines the biology and culture of tilapia in relation to the challenges faced by PNG, Timor-Leste and Solomon Islands and suggests pathways toward cost-effective development and increased food security for these countries.

1.1 Global tilapia aquaculture

Aquaculture provides the majority of global inland fishery production (59.1 million t in 2022). Tilapia and other cichlids (mainly genetically improved farmed tilapia, such as GIFT and the species *Orechromis niloticus*) is the third most abundantly farmed finfish species group (6.5 million t in 2022) behind carps (grass carp (*Ctenopharyngodon idellus)* and silver carp (*Hypophthalmichthys molitrix*)) and catfishes. Tilapia is farmed in more countries than any other species group (FAO 2024).

Tilapia has been widely translocated outside its native range and was coined 'the most important aquaculture species in the 21st century' (Fitzsimmons 2000). When tilapia culture first emerged a few decades ago, it was hailed as the era of the aquatic chicken and the accolades continued as tilapia has become one of the most important food fishes on the planet (Fitzsimmons and Martinez-Garcia 2013).

Tilapia is a common name that is applied to several genera and species of fish that were formerly classified in the genus *Tilapia*, in the family Cichlidae. They are now split into 3 genera: *Oreochromis, Sarotherodon* and *Tilapia* (El-Sayed and Fitzsimmons 2023). The Nile tilapia (*O. niloticus*) and its numerous hybrids, such as blue tilapia (*O. aureus*) and Mozambique tilapia (*O. mossambicus*) are the most widely cultivated. Nile tilapia has been genetically improved for aquaculture objectives (Pullin 1988; Pullin and Capili 1988; Gupta and Acosta 2004; Gupta et al. 2004).

In 1988, a 10-year collaborative research project titled 'Genetic Improvement of Farmed Tilapias (GIFT)' led by WorldFish demonstrated more than 80% production improvement due to selective breeding (Prabu et al. 2019). A faster growing, synthetic Nile tilapia aquaculture strain was created as a result of the GIFT project (Acosta and Gupta 2010). The GIFT strain and the technical approach demonstrated through the GIFT project has since served as a valuable resource for public and private genetic improvement and distribution programs (Eknath and Hulata 2009) with several genetically improved tilapia strains now available and in some cases widely distributed globally.

Although they are not indigenous to Asia, tilapias have long played a vital role in the region's inland fisheries and aquaculture (Prabu et al. 2019). With a spread that is second only to common carp globally, they have been introduced into more than 90 different nations and are now farmed in 126 countries. The majority of production comes from developing countries with large populations. China is the major producer, followed by Indonesia, Egypt, Brazil, Bangladesh, Vietnam, Philippines and Thailand (FAO 2022).

The demand for Nile tilapia is increasing worldwide, especially in developing countries (Asiedu et al. 2015). The market for tilapia is also rising in countries without traditional tilapia production, particularly those with markets that rely on whitefish species (Asche and Zhang 2013). Tilapia production is targeted largely to domestic consumption, but substantial amounts are exported and traded internationally (El-Sayed and Fitzsimmons 2023). The global trade of tilapia has grown significantly over the past 20 years, with sales in over 135 countries worldwide and a predicted continuation of this increasing trend (El-Sayed 2020).

Tilapia are primarily herbivorous and detritivorous feeders and their flexible and opportunistic feeding behaviour make them ideal for aquaculture (Karim et al. 2017). In addition, the species has few major diseases, is tolerant of a poor water quality, adapts well to a range of culture locations and conditions, and the techniques for breeding, feeding, harvesting and marketing are very well established, keeping production costs low and enabling widespread adoption from subsistence farmers to highly intensive commercial enterprises. Fingerlings accept inert feed right after yolk sac absorption (Fracalossi and Turchini 2022). Their lower production costs and market unit values in comparison with carnivorous finfish species allow tilapia to make crucial contributions to food security, nutrition and agricultural development (FAO 2022; De Silva et al. 2004). Due to the affordable price, good quality and simple farming technique, the fish is helping benefit a wide variety of communities in Asia, Africa and Latin America.

These characteristics explain why the global growth in production of tilapia has been so rapid.

1.2 Tilapia aquaculture in Pacific island countries and Timor-Leste

The effects of climate change, including ocean acidification, ocean warming, stronger cyclones and a rise in sea level resulting in the degradation of coral reefs and the decline in coral reef and coastal fish populations in several Pacific island countries is widely projected, with declines expected to continue into the future (Bell et al. 2013). For many coastal communities in Pacific island countries, reef fish and coastal fisheries are a crucial source of nutrition and livelihood. Hence, their decline contributes to poverty and food insecurity as well as increased rural malnutrition, particularly among vulnerable populations like pregnant women and children (Grieve et al. 2013; Susumu et al. 2014). Contrary to coastal fisheries, freshwater aquaculture, particularly tilapia, will benefit from climate change in Pacific island countries. As air temperatures and rainfall rise, the environment should become more favourable for Nile tilapia farming. Higher temperatures may result in quicker rates of growth, allowing tilapia to be farmed at higher elevations in PNG. Higher rainfall might also enable tilapia aquaculture in rain-fed ponds on some atolls (Bell et al. 2013).

Many countries started reinvesting in tilapia aquaculture in the 1990s and early 2000s, following largely unsuccessful projects in the 1960s and 1970s and an awareness of declining coastal fisheries productivity (Ponia 2010). The growth of tilapia aquaculture in Pacific island countries is highly supported from the national to the regional level in terms of development policies and strategies (Secretariat of the Pacific Community 2015; Fiji Ministry of Fisheries and Forestry 2024; Ministry of Development Planning and Aid Coordination 2016). These policies and strategies demonstrate the governments' dedication to promoting small-scale tilapia aquaculture projects to supplement coastal fisheries fish output, provide job opportunities and improve food security for the Pacific (Harohau 2020).

The Mozambique tilapia (*O. mossambicus*) was brought from Africa to Pacific island countries during the 1950s. However, disadvantages with Mozambique tilapia aquaculture include low fecundity, early maturity, early reproduction, sluggish growth and stunting. This results in low yield of small fish that may be difficult to sell, and consequently does not meet the need for either income or nutrition for tilapia farmers (Harohau 2020). In addition, Mozambique tilapia has been associated with a drop in indigenous species (Pickering 2010). Because of these factors, some Pacific island communities have been focusing on the Nile tilapia (*O. niloticus*) – especially GIFT – because of its faster growth rates and larger size. This is further enhanced by the development and implementation of single-sex all-male populations that maintain growth to a larger size due to delayed maturation (Belton 2009).

Tilapia aquaculture has mainly expanded in remote areas for food security and has not yet significantly contributed to private-sector-led economic growth and employment. However, that is now changing in some Pacific ACP [African, Caribbean and Pacific] states, and there is scope for production to grow (Amos et al. 2014). Tilapia was imported by several Pacific islands countries for various objectives. While tilapia was introduced into PNG and Fiji in order to supply fish to rural fish farmers (Smith 2007; Vereivalu 1989), it was primarily introduced into Vanuatu and Solomon Islands in order to reduce mosquito populations and improve inland fisheries (Eldredge and Humphries 1994;

Ponia 2003). Only the tilapia aquaculture industry in Fiji and Guam has so far been transformed into one that is commercially oriented. The majority of tilapia production is for household food security in other countries such as PNG, Solomon Islands and Samoa, where the industry is very much subsistence oriented (Harohau et al. 2016; Mather and Nandlal 2013; Pickering 2015, 2016; Smith 2007).

However, despite the enormously positive contribution of food and income security for many people, especially in developing countries, not everything about tilapia is positive. In areas where they have been introduced, tilapia can sometimes out-compete and negatively affect native species and disturb natural habitats.

In Australia, tilapia were probably first released as unwanted aquarium fish, and *O. mossambicus* is now established in catchments in tropical and subtropical Australia. Black mangrove cichlids (*T. mariae*) has also become established in north-east Queensland. Both tilapia species are declared invasive pests in most Australian states (Queensland Government 2024). They are listed as a notifiable pest under NSW legislation meaning it is illegal to possess, sell or move tilapia (NSW Government n.d.).

These concerns mean the risk of tilapia becoming an invasive species must be carefully managed, particularly in countries where they have not already been introduced. While this does not include PNG, Solomon Islands or Timor-Leste, where tilapia have long been established, opposition from international agencies to tilapia farming in areas outside their natural range, including Pacific island countries, can be a barrier to progress. Where tilapia do exist, introducing GIFT or other genetically improved strains, carefully managing broodfish and only stocking ponds with single-sex fingerings will help prevent negative impacts and moderate criticism of the species.

The characteristics of tilapia aquaculture in PNG, Solomon Islands and Timor-Leste, together with challenges and opportunities are summarised in **Table 1**.

Table 1 Tilapia aquaculture in Papua New Guinea, Solomon Islands and Timor-Leste

	Papua New Guinea	Solomon Islands	Timor-Leste
Production volume in 2020 (tonnes)	1,300	4	More than 500 (2024)*
Number of farmers	60,000 (2018)	150 (2023)	More than 2,500 (2024)
Species	Nile tilapia (GIFT)	Mozambique tilapia	Nile tilapia (GIFT)
Scale of production	Mostly subsistence farming but there is the emerging trend of a small but growing commercialised tilapia production sector at the small to medium enterprise (SME) level in peri-urban areas.	Subsistence production.	A number of rural SMEs have been established across the municipalities involved in the Partnership for Aquaculture Development in Timor-Leste (PADTL) project. The project is being implemented in 7 of the country's 13 municipalities. The Timor-Leste aquaculture development model could be replicated in other countries with similar contexts, especially the small island developing states (SIDS) (Pant et al. 2024a, Pant et al. 2024b, Pant 2023).
Farm productivities		Generally less than 1 t/ha/year.	4.3 t/ha/year (using farm-made feed) and 12.4 t/ha/cycle (6 months) when using commercial feed pellets (Pant et al. 2024a).
Markets		80% of the production is consumed by households, 20% is sold for income.	33% was eaten by households and the rest was sold. Local Service Providers (LSPs) and live tilapia market operators supported by the PADTL play vital role in input supply and output marketing.

Table 1 Tilapia aquaculture in Papua New Guinea, Solomon Islands and Timor-Leste *(continued)*

	Papua New Guinea	Solomon Islands	Timor-Leste
Policy		Strengthening policies governing tilapia aquaculture in Solomon Islands in: • importing quality seed (GIFT tilapia) • hatchery infrastructure for GIFT core breeding population and distribution • small tilapia enterprise development • capacity building • public–private partnerships.	The government of Timor-Leste has national aquaculture development strategy (2012–30) and the government, in partnership with non-profit organisation and donors (WorldFish, New Zealand's Ministry of Foreign Affairs and Trade, USAID, etc.) has been promoting small and SME scale GIFT farming across 7 out of 13 municipalities to strengthen food and nutrition security, creating employment and income opportunities for the citizens of Timor-Leste. Other international non-government organisations (Mercy Corps, CRS) are also promoting tilapia farming in homestead ponds in a number of municipalities.
Constraints for limited contribution of tilapia aquaculture	• Lack of capability within management agencies to identify appropriate sites for pond development. • Inadequate supply and poor quality of fingerlings. • Limited availability and high cost of pond fertilisers and suitable feeds. • Lack of knowledge and training on aquaculture husbandry skills. • High price of imported feeds.	• Lacks a productive tilapia species. • Lack of domestic market development for tilapia. • Lack of knowledge about husbandry practices, feeding and pond maintenance. • Limited extension services provided by national or provincial government.	• Limited availability of affordable concentrate feed. Despite established feed importation and marketing systems by PADTL to facilitate farmer access, imported fish feed pellets remain costly. Although the government and NGOs provide partial subsidies for seed and feed in the initial production cycle to ease transition, the quantities are insufficient, resulting in a shortage of affordable feed for fish farmers. • Timor-Leste's GIFT brood fish management system, supported by government hatchery in Gleno, and 4 public–private partnership models (hatcheries produce high-quality monosex GIFT seed). However, these facilities cannot meet the annual demand of 30 million fingerlings needed to achieve the national strategy goal of 12,000 t of aquaculture production by 2030.

* Noted in Ministry of Agriculture, Livestock, Fisheries and Forestry (MALFF) 'Rapid Assessment of Aquaculture Situation in Timor-Leste (RAAS-TL)', (June–July 2024) Report, and Partnership for Aquaculture Development in Timor-Leste Project (Phase 2).

Catch from a fish pond, Solomon Islands.

2 Role for tilapia aquaculture and socioeconomic challenges

Cage-based fish farming in Yonki Reservoir has grown due to subsidised imported feeds, PNG.

2 Role for tilapia aquaculture and socioeconomic challenges

Despite overall progress during the past few decades, many Pacific island countries face persistently high levels of poverty and lag in achieving most UN Sustainable Development Goals (SDGs) (SDG Gateway 2023), a situation recently exacerbated by the COVID-19 pandemic (IFRC 2023). A recent assessment of SDG progress in the Pacific estimates 42 more years will be required to achieve the SDGs, missing the 2030 target by several decades, unless efforts are multiplied substantially by 2030 (SDG Gateway 2023).

Coastal ecosystems and capture fisheries are critical to the livelihoods, economies, health and nutrition of Pacific island countries throughout the region (Roscher et al. 2022). But with diverse and increasing pressures on capture fisheries and the growing threats from climate change, the role of aquaculture has received increasing attention in many Pacific island countries as a diversified livelihood strategy (Hiruy and Eversole 2020; Harohau et al. 2020), a strategy to address shortfalls in fish supply (Bell et al. 2009), a means of securing healthy and sustainable diets and nutrition (O'Meara et al. 2023) and an economic opportunity (Pickering 2010), including for women farmers and traders (Garcia-Gomez et al. 2018). Throughout the region, various government policies have been enacted to grow aquaculture, often stimulated by regional bodies such as the Secretariat of the Pacific Community (SPC) (Pickering 2010).

The crucial role of fish in nutrition and health has received increasing attention globally (SPC 2022) and in the Pacific (O'Meara et al. 2023; Hiruy and Eversole 2020). While capture fisheries are widely regarded as critically important for nutrition in Pacific island countries, the role of aquaculture in addressing shortfalls in fish supply resulting from population growth, stagnating wild fisheries and climate change have been highlighted (Bell et al. 2011). In an influential analysis, Bell et al. (2009) projected a regional shortfall of 100,000 tonnes of fish by 2030 and proposed tilapia aquaculture as one of 3 ways to meet growing supply gaps (others related to capture fisheries management). This research noted climate-induced changes in rainfall would actually favour inland aquaculture development (Bell et al. 2009) and noted that Solomon Islands and PNG were among the top 3 of 11 Pacific island countries and territories (the other being Fiji) where coastal fisheries will not supply the fish needed for food security in 2030. More specific country studies provide further insights into the potential significance of tilapia aquaculture for food security.

In Solomon Islands, fish supply–demand modelling (Cleasby et al. 2014) suggested a high degree of socioeconomic acceptance of tilapia in diets and shortfalls of 6,000 to 20,000 tonnes of fish that might be met by tilapia aquaculture by 2030. The research noted that the existing low-productive Mozambique tilapia as being unlikely to make significant contributions, further confirmed by Harohau et al. (2020) who noted limited influence of *O. mossambicus* in household diets, pointing towards the need for a more productive strain such as Nile tilapia.

In PNG, there are more than 60,000 tilapia farms, mostly farming Nile tilapia, with many located in remote highland regions, focused on household-level subsistence production. In these regions, tilapia production has become recognised as an important source of much-needed household animal protein (Sammut et al. 2024).

In Timor-Leste, fish supply–demand estimates have projected significant shortfalls in fish supply and identified inland aquaculture, and specifically tilapia, as a key strategy to meet demand and raise per capita fish consumption (Ministry of Agriculture and Fisheries, National Directorate of Fisheries and Aquaculture 2013), with subsequent investments in Nile tilapia (GIFT) contributing to increased fish supplies and improvements in household consumption in farmers adopting tilapia aquaculture (Pant et al. 2023).

However, it is probably fair to say though that while several nations identify tilapia aquaculture and there appears to be widespread socioeconomic acceptance (Garcia-Gomez et al. 2018), actual progress at the scale needed has been limited at best, with evidence of its livelihood contributions mixed.

In Solomon Islands, Harohau et al. (2020) confirmed the social and economic acceptance of Mozambique tilapia, but a limited contribution of tilapia aquaculture to food and income that stemmed from the low productivity of the available tilapia species and the low local demand for tilapia at rural markets. In PNG, tilapia aquaculture has become a self-sustaining largely subsistence activity in earthen ponds in several highland regions, though the isolation of many farm sites and a lack of financial and physical resources limits scaling of production in many rural areas. Although small-scale farming objectives can be met in PNG, such as providing for family and dietary requirements, the availability and cost of feed is seen as a barrier to more commercial-scale production. Furthermore, even though fish farming is extensively practised in PNG, farm yields are often poor when compared to Asia. The main bottlenecks for increasing fish production and impacts on livelihoods in PNG include poor access to commercial feed and feed ingredients, lack of fish husbandry skills and poor-quality fingerlings (Sammut et al. 2021).

The aquaculture industry in Timor-Leste is still in its early stages, but Nile tilapia production has grown following the introduction of Nile tilapia GIFT in 2015 (Pant et al. 2020). The rural economy benefited from inland fisheries under the Indonesian administration, notably tilapia and carp, but these operations ceased after the country's independence in 1999 when numerous aquaculture facilities were destroyed. Since then, the government has steadily revived aquaculture activities with assistance from subsidies of external organisations. Tilapia is currently one of the most common farmed freshwater species in Timor-Leste, with small-scale pond farming contributing to homestead food production and incomes in several parts of the country (Pant et al. 2019). Tilapia value chains are also starting to develop in the country, with connections being made from more commercially oriented small-scale farms to markets, and some intermediary businesses emerging, likely creating additional livelihood opportunities.

For tilapia aquaculture in PNG, Solomon Islands, Timor-Leste, and indeed many Pacific island countries, a range of different culture systems and intensities characterise production. The model at **Figure 2** represents one way of understanding the differences. In this model, production is described as *subsistence, community, small-scale commercial* and *large-scale commercial.* These descriptors align with more traditional culture type descriptors of *extensive, semi-extensive, semi-intensive* and *intensive*, in that order. A model such as the one proposed is useful to help understand how different approaches/solutions are needed to address some of the fundamental challenges that face all production types. It should be stressed that the categories are often more of a continuum than clear differences and that farmers move from one category to another depending on circumstance.

	Production focus			
Characteristics	Subsistence	Community	Small-scale commercial	Large-scale commercial
Culture type	Extensive	Semi-extensive	Semi-intensive	Intensive
Fingerling supply	Purchased	Purchased	Hatchery/ purchased	Hatchery
Feeds and feeding	Natural/ supplemented	Supplemented/ on-site farm made	On-site farm made	Commercial pellets
Production platforms	Small pond(s)	Larger pond(s)	Multiple ponds or cages	Large number of cages or ponds
Economic drivers	Self-consumption	Self-consumption and trade	Financial income	Business income/ employment
Monitoring	Observation	Feed volume/ observation	Oxygen/ feed volume/ growth rates	Water quality/ growth/feed efficiency
Management	Reactive ←		→	Proactive

Figure 2 A model for inland aquaculture in Pacific island countries and Timor-Leste

For example, a subsistence farm might be primarily used for on-farm consumption but any fish in excess to requirements might be sold or traded. Production for food and production for income are both of priority, depending on where the farms are located, resource availability, markets and business opportunities.

It is often assumed that large-scale commercial production is the goal, but this is overly simplistic. The best production system is the one that best suits the people that rely on the fish for nutrition or income.

A large-scale commercial farm might actually negatively impact on the availability of tilapia for food in communities without a functioning money-based economy, like many places in remote PNG. That said, a focus solely on subsistence-type farming risks failure in meeting national food security requirements (Cleasby et al. 2014), including the development of market-oriented value chains and market systems that can supply the fish requirements of urban populations.

Aquaculture in Pacific island countries, including tilapia aquaculture, has received limited attention from a gender perspective (Garcia-Gomez et al. 2018), though SPC research in Fiji and Samoa (SPC 2023) reveals the significant role of Pacific women in the management of aquaculture activities, which is often not recognised and not valued. Findings to date suggest that as is traditional for other rural agricultural practices, tilapia farming in both countries has a very pronounced gendered division of labour. Women in both countries reported benefits from small-scale pond tilapia aquaculture from cash income for their personal needs and community obligations, often in places where there are no other alternative income sources for women. This limited information suggests more attention should be given to the roles and potential roles of women in future development of tilapia aquaculture.

Finally, small-pond aquaculture of tilapia can make contributions during post-cyclone recovery and rehabilitation of fisheries-dependent communities in the Pacific. One of the dramatic impacts of Cyclone Winston in Fiji during 2016 was a sharp reduction in consumption of fresh fish (Chaston Radway et al. 2016). Tilapia from ponds provided the only source of fresh animal protein available in the initial 2 to 3 months post-cyclonic disaster, with communities widely recognising tilapia aquaculture as an important livelihood activity post-cyclone in the provinces of Cakaudrove, Tailevu and Lomaiviti (Chaston Radway et al. 2016).

The socioeconomic impacts from tilapia aquaculture have long been anticipated for Pacific island countries since at least 1950, but progress has been slow due to unsuitable initial choice of species, logistical constraints due to the Pacific's fragmented geographies, lack of technical capacity and other factors (Garcia-Gomez et al. 2018). The future effects of climate change in the south-west Pacific are predicted to be beneficial for tilapia aquaculture, and fish supply shortfalls are likely to get worse. Available insights suggest that tilapia can play an increasingly prominent role in food and livelihoods in Pacific island countries, in a future where over-fishing, environmental degradation, and the projected impacts of climate change will continue to pressure fish resources and communities. The challenge now is to move to implementation at the scale needed and in ways that optimise socioeconomic benefits to farmers, farm households, communities and wider national development goals.

2.1 Recommendations

- Improve knowledge on rural and urban markets and value chains to drive investment strategy.
- Update projections about the fish supply shortfall for the Pacific, including better insights on socioeconomic impacts (for example, income, nutrition and gender).
- Examine the role of tilapia for fish supply and identify socioeconomic characteristics that might affect potential growth.

3 Fingerling production: status, challenges and opportunities

Average size of Mozambique tilapia at harvest, Solomon Islands.

A fish farmer next to her aquaculture pond,
Solomon Islands.

3 Fingerling production: status, challenges and opportunities

3.1 Tilapia fingerling production

Tilapia fry and fingerlings, of sufficient quality and quantity, are a prerequisite for successful tilapia aquaculture. The present supplies of tilapia fry and fingerlings in PNG, Solomon Islands and Timor-Leste, and elsewhere in Pacific island countries, come from a mix of sources. These include hatcheries and/or nurseries (PNG, Timor-Leste and other Pacific island countries), collection of fry and fingerlings from the wild (occasionally with *O. mossambicus* in Solomon Islands) and from self-reproduction in fish farmer ponds *(O. mossambicus* in Solomon Islands and Nile tilapia *(O. niloticus*) in PNG).

The Mozambique tilapia (*O. mossambicus)* has been widely distributed throughout Pacific island countries since the 1950s, but poor growth performance and inbreeding have led to interest in introductions of faster growing Nile tilapia derived strains (Pickering 2010). Solomon Islands is one of the few Pacific countries still without Nile tilapia, but in PNG, Timor-Leste, Fiji and elsewhere, various Nile tilapia derived strains have been introduced during the past 30 years; the GIFT strain to Timor-Leste in 2016 by WorldFish; various strains to PNG; Thai strains to Vanuatu; and GIFT, Israeli, the Thai strain Chitralada and red tilapia hybrids to Fiji (Macaranas et al. 1997). These Nile tilapia derived strains and genetics have originated from international research organisations (for example, WorldFish), and commercial genetics companies and hatcheries in Thailand, Israel and possibly other countries. These improved strains are normally managed with limited capability and facilities to maintain genetic quality, commonly resulting in a gradual genetic deterioration, with longer-term implications for farmer productivity and incomes and overall efficiency and sustainability of tilapia aquaculture.

Tilapia hatcheries with capabilities to hold tilapia broodstock, breed and distribute tilapia fry and fingerlings can be found across the region, although they are by no means common. The hatchery types for Nile tilapia range from specialised centralised hatchery structures – often operated by government and holding a 'nucleus' of tilapia genetics, such as in PNG and Timor-Leste – to private- and public-owned satellite hatchery and simple pond-based systems for fry and fingerlings production, such as found widely and operated by farmers, NGOs or communities throughout the highland regions of PNG. A new government-operated hatchery facility has recently been constructed in Solomon Islands in preparation for the introduction of Nile tilapia following a government policy decision to introduce a better performing tilapia. The ownership and management of hatcheries includes both public, civil society/NGOs and private-sector farmers and investors.

Monosex technology to produce all male fry exists in PNG, Timor-Leste and Fiji although problems in accessing the hormones required, and even the technical skills, are sometimes reported. In all countries, tilapia are distributed to farmers locally and across wider networks, as small fry (~1 inch size) or larger fingerlings (~2–3 inch size) depending on farmer demand, geographies and management practices.

In PNG, central government operates tilapia hatcheries, with distribution networks involving private or NGO/community-run 'satellite' hatcheries. The National Fishery Agency has established 22 satellite hatcheries in 18 provinces across the country, of which 5 are applying sex reversal technology. This wide network of satellite hatcheries has apparently contributed to the increase in fish farming activities in local areas. Farmers can now access tilapia fingerlings that were previously not readily available, and reports of success have attracted new farmers, a key factor enabling the growth of tilapia aquaculture, with 66,000 fish farmers now found in PNG (Noiney 2024).

In Timor-Leste, central government operates a centralised hatchery facility, with technical and financial assistance from WorldFish and the New Zealand Government in the initial years. The centralised hatchery maintains a core GIFT population and is responsible for distributing broodstock and fry and providing technical assistance to a small number of public-private partnership model hatcheries and nurseries. WorldFish is providing private hatcheries with partial funding for establishment of hatchery and training and mentoring support to encourage a private-sector-oriented tilapia fingerling supply with the objective of stimulating greater sustainability through a market-oriented approach beyond grant-funded projects (Pant et al. 2023).

The operational capacities of tilapia hatcheries in PNG and Timor-Leste are generally small, ranging from a few thousand fry or fingerlings per year to a few million. The small satellite hatcheries in the PNG highlands are examples of how satellite hatcheries can stimulate localised tilapia farming production. Distribution networks tend to be not well organised and not as well developed as in Asia. The volumes of fry and fingerling production overall are difficult to estimate, but a region-wide production of ~1600 t/year of farmed tilapia would suggest around 12.8 million fingerlings/year (assuming 250 g market size and 50% survival from egg to harvest). Meeting a stepwise increase in region-wide production of tilapia would clearly need a significant increase in investment in fry and fingerling production and networks that facilitated widespread access for farmers.

The pond yield performance of tilapia fry and fingerlings are poorly documented, though some estimates are available. In Solomon Islands, Mozambique tilapia yields in ponds were very low, generally several kilograms per year (Harohau et al. 2020). In PNG, data on yields of Nile tilapia derived strains were not available. In Timor-Leste, average yields have grown from 4.3 t/ha/year (fed with farm-made feed) to up to 16 t/ha/cycle (6 months) with feeding commercial feed pellets and technical assistance (Pant et al. 2023; Pant et al. 2024). Yields are likely to be highly variable, related to the tilapia strain used and degree of genetic deterioration, stunting, maturation, feeding and fertilisation practices and overall management (Harohau et al. 2020). No Pacific regional source of improved tilapia genetics is available, though proposals have been made by SPC to establish a Pacific regional source of improved tilapia genetics for distribution within the region (Pickering 2010).

3.2 Specific challenges to production and distribution

- Fragmented value chains that could be overcome to some extent by localised production of tilapia seed, such as through the decentralised hatchery and satellite networks in PNG.
- Access to hormones needed for monosex production systems.
- Lack of genetically improved strains that are widely accessible to farmers in the region and challenges in maintaining genetic quality of stocks. This might be overcome by establishing a regional broodstock and distribution centre, perhaps with associated technical supporting functions (Pickering 2010).
- Biosecurity risks associated with introductions of tilapia to the Pacific region, and maintaining the overall status of the region as free of important tilapia diseases. A biosecure regional broodstock centre might reduce any risks.
- Lack of capacity to manage hatcheries and genetics.
- Government-owned facilities with low incentive to produce high-quality fry and build a market.
- Limited private-sector involvement in hatchery production due to constraints in skills and investment capacity.
- Business case (and incentives) for private-sector engagement in hatchery production. The start-up grants and training being offered by WorldFish in Timor-Leste might be an example of how the private sector can be better supported to invest in hatchery businesses (where sufficient market exists) (Pant et al. 2024).

Why isn't existing technology sufficient?

The technology is probably sufficient to maintain current levels of largely subsistence production but is unlikely to be sufficient to supply tilapia fry and fingerlings at the scale needed for growth.

3.3 Recommendations

- Improve genetic management of tilapia, including the importation of better genetics (such as GIFT) into Solomon Islands and broodstock management in other countries.
- Increase adoption of single-sex production of fingerlings by increasing access to essential chemicals and equipment.
- Create incentives and strategies for the private sector to invest in tilapia hatcheries and small-scale satellite hatcheries. Support promising entrepreneurs to develop hatchery and nursery businesses.
- Focus on capacity building and training.

Summarised in **Figure 3**.

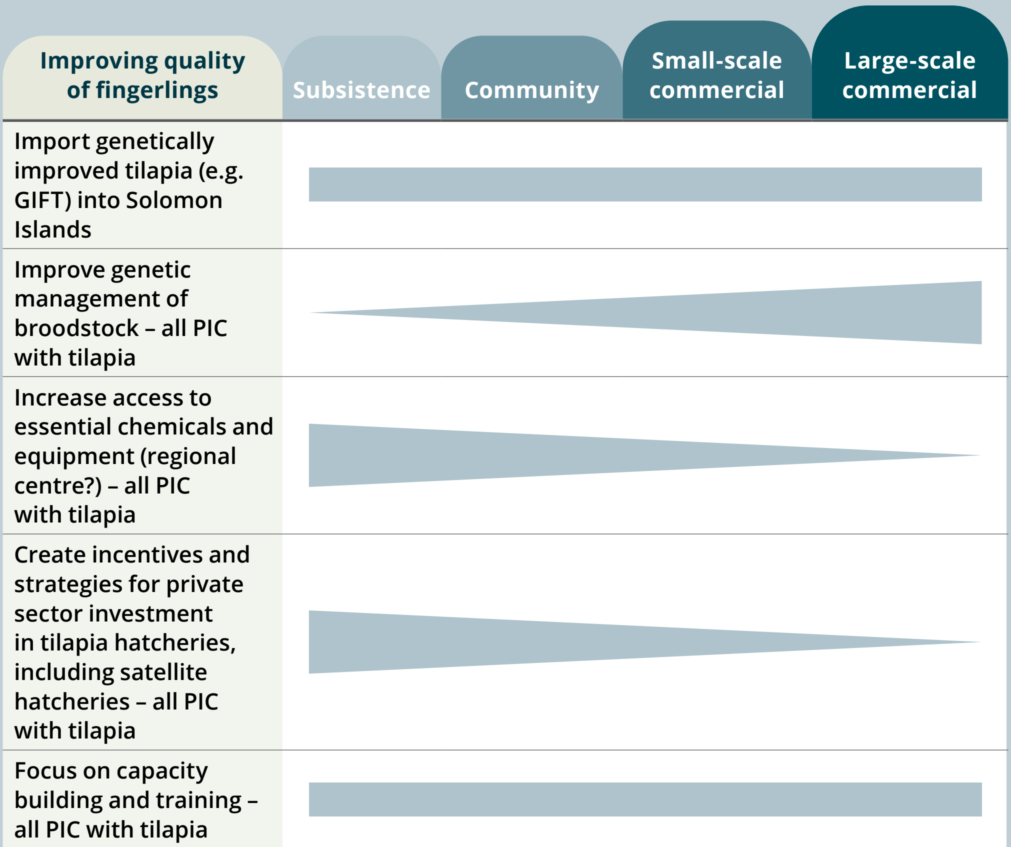


Figure 3 Recommendations to improve quality and availability of tilapia fingerlings

Note: The size of the block indicates relative importance for each type of farm – for example, improving genetic management of broodstock is increasingly important as scale of farm increases. PIC = Pacific island countries.

4 Feeds and feeding: status, challenges and opportunities

A farmer feeding fish in Batugade, Timor-Leste.

4 Feeds and feeding: status, challenges and opportunities

4.1 Priorities for feeds

Nutrient requirements in aquaculture are typically defined by the optimal response in manipulative experiments (Shearer 2000). These responses almost always involve growth measures, but feed efficiency and physiological measures also contribute to our understanding of optimal nutrient balance in feed formulation. A comprehensive summary of nutrient requirements for tilapia is provided by Booth (2017). Nutrient requirements for optimal growth in controlled tank conditions often overestimate nutrient requirements for pond-based aquaculture, depending on the nutrients available from the pond ecosystem (Tacon 1995). Excess nutrients from the feed contribute to pond productivity, either by fertilising plants, directly feeding other organisms in the pond, contributing to bacterial biomass production or settling as detritus that can perform any of the above functions or act as a reservoir of feed for detritivores (Narimbi et al. 2018). However, the ecosystem is variable between ponds as well as between farms, posing a challenge to define the appropriate quantity and balance of nutrients required in a feed to supplement the pond food web. The relative contribution of natural productivity to the nutrient requirements of tilapia is also likely to shift with production intensity and stocking density, making optimal formulation for pond environments extremely challenging (Lovell 1989).

Optimised production may not be the goal of all farmers, particularly in subsistence aquaculture where tilapia is grown at relatively low densities for food rather than for profit. Trade-offs between feed cost, form (pellets or granulated ingredients) and availability of feeds will likely dictate their use. At higher production intensity, high-quality feeds are necessary to optimise production speed and efficiency, while at low stocking density in pond environments, there is a clear trade-off between the benefit of feed, its cost and the nutrient value of pond productivity. Clearly, a different approach to feed and feeding is required to cater to different tilapia farmers; from low-density to high-density pond production, as well as higher-intensity farming which contributes to natural food production. **Figure 4** lists some of the different feeding resources that might be considered for different types of tilapia farms.

Feed resources	Subsistence	Community	Small-scale commercial	Large-scale commercial
Fertilisation (manure)	✓			
Insect supplements	✓	✓		
Supplementary feeds (local ingredients)		✓	✓	
Farm-made feeds (mini-mills)		✓	✓	✓
Concentrates (mini-mills)			✓	✓
Imported commercial feeds			✓	✓
Capacity building – training	✓	✓	✓	✓
Capacity building – internships			✓	✓
Capacity building – government	✓	✓	✓	✓

Figure 4 Feed resources for different types of tilapia farms in Pacific island countries and Timor-Leste

4.2 Appropriate and available raw materials for feeds

Tilapia are able to utilise a variety of feed forms, ranging in size and form, from microscopic algae and bacteria particles, to detritus and complete feeds. They are therefore particularly suited to utilising nutrient sources that are cheaply available, but not necessarily complete. Formulated feed may not be the major contributor of nutrients for the growth of pond-reared tilapia; however, supplementary nutrients in excess of those delivered by the pond environment appear to be necessary to optimise production (Diana et al. 1996; Narimbi et al. 2018; Salger et al. 2020). The appropriateness of feed materials depends on their nutrient value, antinutrient content, cost, availability and ability to be stored and processed. These feed materials can either be used as supplements to enhance the nutrients available from pond productivity, as supplements to formulated feeds, or as complete formulated feeds.

Availability and cost of suitable feeds are high on the list of the main challenges facing tilapia farmers in PNG, Solomon Islands and Timor-Leste. Feeds are also a problem constraining tilapia aquaculture growth throughout Pacific island countries.

There are many reasons the challenges with feeds are particularly acute in the region:

- Small industry and low demand for commercial aquaculture feeds. No modern commercial aquaculture feed manufacturers have plants in PNG, Solomon Islands, Timor-Leste or any other Pacific island country.
- High cost of importing aquaculture feeds, and feed ingredients like fishmeal, from neighbouring countries. This is due to low demand (lack of economies of scale), poor shipping infrastructure and logistical and ground transport difficulties.
- Limited availability of local feed ingredients with potential for use in locally made feeds. This is especially true for protein sources but applies to lipid sources and micronutrients. Even the available carbohydrate sources are often of poor quality and are not always available where and when needed (Pant et al. 2023).
- There are commercial animal feed manufacturing plants, primarily for poultry, in PNG, and Fiji, but in general they are small-scale and do not have extrusion capacity and, with the high cost of imported ingredients, like high-quality fishmeal, they struggle to produce quality aquafeeds that are also cost-effective.
- Almost all the tilapia farms are small-scale with low purchasing power. Until demand for feed increases, economies of scale will mean, in general, tilapia farmers in PNG, Solomon Islands, Timor-Leste and elsewhere in Pacific island countries will pay a premium for feeds. There are nascent farmer collectives in PNG and Fiji and as these develop the ability to negotiate more favourable feed contracts will improve.
- Distribution, transport and storage infrastructure for aquaculture feeds make delivery to farms in PNG, Solomon Islands, Timor-Leste and many other Pacific island countries more difficult and expensive than in other countries.

There are several options to address these challenges for tilapia farmers, all with positives and limitations, a summarised in **Table 2**.

Table 2 Options for feeding strategies, suitability for different production focus, and positives and limitations

Option	Approximate production potential (t/ha)	Production focus	Positives	Limitations
Natural feed (fertilisation)	<1	Subsistence and community	• Low cost; no need for feed manufacture or storage. • Suitable for 'low cash' farms, ease of management.	• Low production, cost and availability of both organic and inorganic fertilisers, if needed.
Local leaf materials	Largely untested	Subsistence and community	• No cost feed additive. • Some nutritional value.	• Tannins and other antinutrients limit use. • Little knowledge of the effect of processing on antinutrients.
Black soldier fly larvae (BSFL) (see Appendix 1) or other cultured feed source	Unknown – assume >3	Subsistence and community	• Relatively low cost; no need for feed manufacture or storage. • Suitable for 'low cash' farms.	• Unproven; need expertise in BSFL (or other) culture. • Additional costs unknown.
Duck weed (perhaps in conjunction with BSFL or other)	2–3	Subsistence and community	• Relatively low cost; would complement BSFL. • No need for feed manufacture or storage. • Suitable for 'low cash' farms.	• Availability of duck weed uncertain. • Expertise needed to manage duck weed culture (e.g. nutrients). • Additional costs unknown.
Agricultural by-products (broken rice, brans, pollard, etc.)	2–3	Subsistence, community and small-scale commercial	• Relatively low cost and no technical requirements. • Increases productivity of ponds and proven cost-effective in several areas.	• Availability and distribution. • Competition with other animal production industries. • Cost may limit the application to subsistence farming unless benefits are demonstrated at a local scale.

Table 2 Options for feeding strategies, suitability for different production focus, and positives and limitations *(continued)*

Option	Approximate production potential (t/ha)	Production focus	Positives	Limitations
Locally made feeds using small-scale equipment in proximity to farm	3–10	Subsistence, community and small-scale commercial	• Lower cost than commercial feeds; transport costs less than for commercial feeds, higher production potential than lower feed input strategies. • Potential to include local feed materials.	• Low capacity to produce locally made feeds. • Difficulty sourcing available ingredients. • Storage of feeds can be hard. • Water stability of feeds poor and potential for adverse effects on water quality.
In-country feeds using large-scale equipment for other animals (e.g. pellet press for poultry feeds)	5–10	Community and small-scale commercial	• Lower cost than commercial feeds; transport costs less than for commercial feeds. • Higher production potential than lower feed input strategies.	• High cost – transport costs high. • Capacity to make quality feeds uncertain (formulation and equipment). • Water stability of feeds not as good as commercial feeds leading to some potential for adverse effects on water quality.
Commercial feeds	>10	Small-scale commercial and large-scale commercial	• Highest production potential. • Highly water stable feeds leading to less concerns with water quality management. • Best feeding option to help understand production capacity of ponds.	• Farmers require training on how to estimate the appropriate amount of feed needed for their fish (Pant et al. 2023).

4.3 Feed resources

Pond fertilisation

Tilapia ponds can be fertilised to contain significant production of microalgae, which is supported by fertilisation and alkalinity adjustments (Salger et al. 2020). This relies on a combination of organic and inorganic fertilisers, which are maintained in the pond ecosystem as long as water exchange is very low (Boyd and Tucker 2012). Algae incorporate fertiliser and waste nitrogen from the fish into algae biomass, which becomes a feed source for tilapia as well as producing oxygen during the day. Unfortunately, dense algae blooms in ponds destabilise water quality through diurnal shifts in oxygen, carbon dioxide and, consequently, pH. Algae respiration provides oxygen during daylight hours, but depletes oxygen overnight (Boyd and Tucker 2012). When overnight oxygen levels are allowed to drop to 10% of saturation, growth of tilapia can be reduced by 20% (Teichert-Coddington and Green 1993). The daytime increase in pH caused by algal respiration increases the proportion of ammonia that is present in the unionised form, which has a higher toxicity to the fish (Boyd and Tucker 2012). Algae crashes can severely deplete pond oxygen levels, while overcast days can also deplete phytoplankton productivity. Therefore, food and water quality are integrally linked and must be considered together.

Variable conditions typical of heavy phytoplankton blooms can be mediated by adding carbon to the pond, usually in the form of simple carbohydrates, to favour bacteria production (Khanjani et al. 2022). This incorporates nitrogen into bacterial biomass that stabilises water quality while also providing a feed source for tilapia, which can feed on the resulting flocculant strings of bacteria (Ogello et al. 2014; da Silva et al. 2020; Khanjani et al. 2022).

Primary productivity of phytoplankton and bacteria also support secondary production of zooplankton, which contribute further to the tilapia feed resource (Diana 2012). Manures are commonly used for pond fertilisation and are considered to be both a primary food source for tilapia and a source of fertiliser for primary and secondary pond productivity (Diana et al. 1991). Primary production may be further supported by adding floating structures in pond and cage systems in order to support periphyton growth, which is then available as a nutrient input source for tilapia (Garcia et al. 2016; David et al. 2022).

Adding feed materials to fertilised ponds

Appropriate nutrient levels and raw materials have been well documented for tilapia in intensive tank-based production systems (reviewed by Ng and Romano 2013). However, relatively little is known about feed materials that best contribute to cost-effective nutrient supply for relatively extensive pond culture. Semi-intensive tilapia production can rely on primary productivity to supply some essential amino acids (Khalil et al. 2021), vitamins and minerals (Liti et al. 2005); therefore, feeds in semi-intensive systems do not necessarily need to be complete, but rather increase the volume of nutrients available. In addition to the direct supply of nutrients, supplementary feeds and feed materials contribute to pond productivity (Narimbi et al. 2018; Kabir et al. 2020), and therefore there can be a fine line between feed and fertiliser for pond-reared tilapia.

Nile tilapia typically derive nutrition from detritus, which is a combination of discrete feed materials and bacteria (Jafri and Ali 1984). Uneaten feed and faeces will therefore contribute indirect nutrition through detritus, where high-quality feed materials will be downgraded to medium-quality bacterial nutrients, and low-quality materials will be upgraded through bacterial production in the detritus. The detrital cycle may be seen as analogous to the internal microbial fermentation of ruminant animals, where high-quality feeds may not be suitable due to nutrient degradation. In contrast, this bacterial-mediated pathway highlights the potential to feed the pond ecosystem through fertiliser and feed materials that contribute to pond productivity and detritus feed stores. There is clearly a trade-off between nutrient inputs and nutrient pollution that must be managed when promoting bacterial growth within a pond.

As tilapia grow, they gradually consume a higher proportion of the available primary productivity. The biomass where fish growth becomes self-limited is known as the critical standing crop. As long as other water quality parameters are not limiting, critical standing crop can then be increased by supplemental food. Therefore, the decline in phytoplankton levels in ponds has been suggested as a trigger for the need for supplemental feed addition, indicating that tilapia biomass has reached the point where their food consumption outstrips pond productivity (Romana-Eguia et al. 2013). Utilisation of agricultural or household by-products is an intermediate step between pond productivity and complete formulated feed (Hinneh et al. 2022). Tilapia can consume a variety of food forms, meaning that powdered or granular feed forms are often appropriate.

As well as indirect nutrition pathways through pond production, tilapia readily consume a range of inexpensive by-products from other industries, including chopped banana leaf, cassava, sweetpotato, cotton seed, wheat husk, oil seed cake and even chopped garden waste (Jafri and Ali 1984; Little and Edwards 2004; Parata et al. 2020). In geographies where rice is commonly grown, its bran is often utilised as a supplemental feed for pond-reared tilapia. Adding rice bran at 2% body weight per day, in combination with inorganic fertiliser, increased the biomass yield of pond-farmed Nile tilapia by 5 to 8 times than achieved by adding manure fertiliser alone (Little and Edwards 2004). While rice bran may be inferior to wheat and maize brans due to lower protein and higher fibre content, the cost of these materials is likely to determine their use in remote low-intensity farm settings (Liti et al. 2006).

Starch-rich feed materials appear to have little direct nutritional value above their energy content, and their use in the absence of available fertiliser (nitrogen, phosphorous and potassium) results in suboptimal growth results (Parata et al. 2020; Parata et al. 2023). However, adding carbon to ponds in combination with these nutrients increases the C:N ratio, favouring bacterial growth that can recapture waste nitrogen into a form that can be readily consumed by tilapia (Ogello et al. 2014). Formulated tilapia feed typically has C:N ratio between 6 and 11, while C:N of 10–20 is required for significant bacteria growth (Khanjani et al. 2022). Bacterial production binds nitrogen in edible biomass, reducing ammonia while increasing feed efficiency (Avnimelech 1999). This benefits production by improving water quality and providing supplementary food that can either decrease the need for formulated feed or decrease the level of protein required for optimal growth using such feed (Avnimelech 1999; 2007).

Feed ingredients plus formulated feed

As production intensity increases to the extent that primary productivity contributes little to tilapia nutrition, farmers rely more on complete formulated feeds. Supplementation of brans alone or low protein (16%) pig feed appear to be able to support optimal growth of tilapia when biomass is below 1,370 kg/ha (Liti et al. 2005, 2006). However, higher protein (24%) feed provided higher growth when standing biomass exceeded this figure (Liti et al. 2005). In semi-intensive production systems, application of formulated feed can increase growth of tilapia 2–4-fold (Salger et al. 2020). Fish yield in excess of 10,000 kg/ha have been reported, with growth rates of 3.1 g/day, with ponds that are both fertilised and fed (50% satiety, 30% crude protein) (Diana et al. 1996).

Formulated feed represents the largest variable cost for fed aquaculture, including tilapia production. In remote areas with poor transport infrastructure, it is particularly important to optimise the use of goods that must be imported and/or transported domestically. Applying domestically available feed materials to supplement formulated feeds is one mechanism by which farmers may stretch the value of formulated feeds.

One such approach has been suggested for PNG, with a centrally made feed concentrate providing the protein, vitamin and mineral supplements, blended on-farm with locally available ingredients such as dried cassava or sweetpotato that provide energy and filler to the diet (Booth et al. 2017). This reduces the load on limited transport infrastructure, since only 60% of the final feed needs to be transported. This approach requires protein-dense raw materials for concentrate formation, which tend to be more expensive per unit of protein than less protein-dense raw materials. The cost-effectiveness of this approach therefore may be limited in circumstances where locally available feed ingredients come at a cost rather than being a cost-free waste product.

Localised bio-concentration of protein may present more opportunities for supporting tilapia growth in areas where transport for formulated feed is problematic and/or inconsistent. Worms and insect larvae can both be produced on organic waste products, concentrating the protein and energy into biological forms that can be directly fed to farmed tilapia.

Production of insects such as black soldier fly (BSF) may also be a viable means of reclaiming waste nutrients from animal manure. While BSFL meal is an excellent raw material for tilapia feeds (Tippayadara et al. 2021; Limbu et al. 2022) its use as a whole fresh or dried larva has not featured prominently in published literature. It is therefore unclear the extent to which whole BSFL may be able to supplement a complete formulated feed. Since insects are rich in both protein and lipid, their potential to supplement formulated feeds likely exceeds more than 50% of their complete diet, depending on micronutrient supplementation.

An additional benefit of BSFL is that they self-harvest. Prepupae migrate out of their feed source before pupating. If placed over a pond, this may be used to automatically feed ponds without the need for direct human intervention. Other insects, such as termites, can also supply protein and other valuable nutrients that can support growth of tilapia. While insects may not be a complete food for optimal production, they are likely to support substantial growth and health of tilapia for subsistence production (see **Appendix 1**).

Duckweed is a promising feed material that can be grown in ponds along with tilapia or in discharge channels, concentrating nitrogenous waste products from fish production and converting it into a relatively protein-rich feed material. Duckweed can support growth of tilapia as a sole feed, however not to the extent of complete formulated feed (Tavares et al. 2010). As a feed ingredient, duckweed can replace up to 50% of a formulated feed without impacting growth (Tavares et al. 2008). Locally available feed ingredients have been reviewed for PNG (Pirozzi et al. 2011; Booth 2017) revealing that relatively low-cost materials that can supplement food from pond fertilisation can come in the form of broken rice, cassava, sweetpotato and leaves.

Complete formulated feeds

Optimising growth and yield of tilapia necessitates the use of complete formulated feed. Likewise, cage or tank systems provide negligible natural feed production and high-quality formulated feed is necessary to support significant growth of tilapia. Indeed, dense phytoplankton blooms in intensive cage culture systems are considered to negatively affect production of tilapia due to their ability to deplete oxygen overnight while not contributing significantly to growth (Conte et al. 2008).

Feed ingredients for farmed fish generally go through a similar trend over the development of species-specific nutritional knowledge. When nutritional requirements for a particular species are relatively underdeveloped, there is generally a high dependence on fish meal to provide most of the unknown nutrient requirements. As these requirements become more established, formulation becomes more flexible and a wider variety of raw materials can be used to formulate a complete feed. These feed ingredients can be of plant and/or animal origin depending on the governing regulations, each with positive and negative aspects that need to be accounted for in formulation.

By-products of animal production often have similar nutrient profiles to fish meal, with terrestrial animal meat products containing amino acid and micronutrient profiles more similar to fish proteins than is possible through plant materials. Terrestrial meat meals of bovine, porcine and avian origin are all suitable for aquaculture production and contribute to cost-effective supply of protein and other nutrients where they have ready availability. Meat meal is the predominant processed animal product that has been identified in PNG other than fish meal (Booth 2017) and it has the potential to supply significant protein into tilapia formulations. Its quality is dictated by the freshness of the product before rendering, the temperature of the rendering process as well as the protein and ash content.

Making use of cost-effective local ingredients that are not directly consumed by humans and supply valuable nutrients for fish can make a valuable contribution for circular economy approaches; however, attention is required to balance macronutrient and micronutrient profiles to ensure health and production outcomes for the farmed fish. Mill run, broken rice, cassava leaf and copra have all been identified as by-products from other food sources that can cost-effectively be incorporated into tilapia feeds in PNG (Booth 2017). Although sweetpotato leaf appears to depress growth when untreated (Sine et al. 2017), heat treatment may improve their antinutritional content sufficiently to make them a useful and cost-effective feed source (Almazan 1995; Mwanri et al. 2011).

The output targets of feed formulation are also variable with species. High-value aquaculture species necessitate a focus on improved growth and feed conversion. While feed is a large cost, the value of fish produced is generally very high compared to the cost of feed, and more costly raw materials and production methods can often be justified if they produce higher growth and therefore more fish. There is obviously a cost-benefit limitation to this equation. In contrast, lower-value fish production often necessitates feed that is suboptimal in relation to growth if the cost of production can be optimised.

4.4 Feeding methods

Tilapia has a relatively small stomach holding capacity, and therefore more frequent feeding is recommended than other species. Six meals per day is recommended to fish less than 1 g in intensive systems, gradually reducing to 3 meals per day for fish greater than 175 g (Ng and Romano 2013). In cages, 90% of satiety balances growth and feed conversion (Conte et al. 2008). In contrast, fertilised ponds often do not require supplemental feeding when tilapia are small, and cost-benefit may be optimised by reducing feed inputs to alternate days (Salger et al. 2020) or daily at 50% of satiety (Diana et al. 1996). In Timor-Leste, over 600 farmers have been trained to estimate fish biomass monthly in their pond and adjust the daily feeding rate for each pond (Pant et al. 2024).

Interactions with other livestock feed production – pig and chicken

Aquafeed typically differs from terrestrial agrifeed in that it must be water-stable, and typically has higher protein and lipid requirements. Tilapia feeds typically contain much lower protein and lipid than those for other fish species, meaning that they more closely resemble terrestrial animal feeds in these respects. The ability of tilapia to generate nutrition from suspended algae, bacteria and surface periphyton means that species-specific nutrient requirements often take a backseat to cost and availability of feed. Opportunity exists to utilise existing supply chains for terrestrial animal feeds when cost of this feed is low and species-specific feed is unavailable or cost prohibitive. This may be a transition strategy into species-specific feeds since terrestrial animal feed mills contain many of the feed materials required for tilapia feeds. Ambitions for growth and stocking density will dictate the need for species-specific feeds.

4.5 Feed production

Appropriate feed production technologies

Aquafeed production aims to provide the appropriate nutrients for the specific size of an aquatic animal, in a format that it can consume and digest. Further refinements optimise shelf-life by drying (ideally to a water activity less than 0.7 aw), modifying float-sink properties to aid feeding management and grinding raw materials to a size that facilitates feed production and optimises digestion. Heating and drying processes remove a number of the antinutritional properties present in plant ingredients (Francis et al. 2001) and promote storage shelf-life at room temperature (Chevanan et al. 2009). Processes of commercial feed manufacture are often optimised for efficiency in a factory setting, while several steps may be removed for local feed manufacture (**Figure 5**). Such feed manufacture is often a trade-off between technological/capital investment, labour requirements and energy requirements (**Table 3**). Intensively managed tilapia production systems often utilise extruded feeds that are efficient to manufacture in large quantities, but relatively inefficient in terms of capital cost and energy inputs at a small scale.

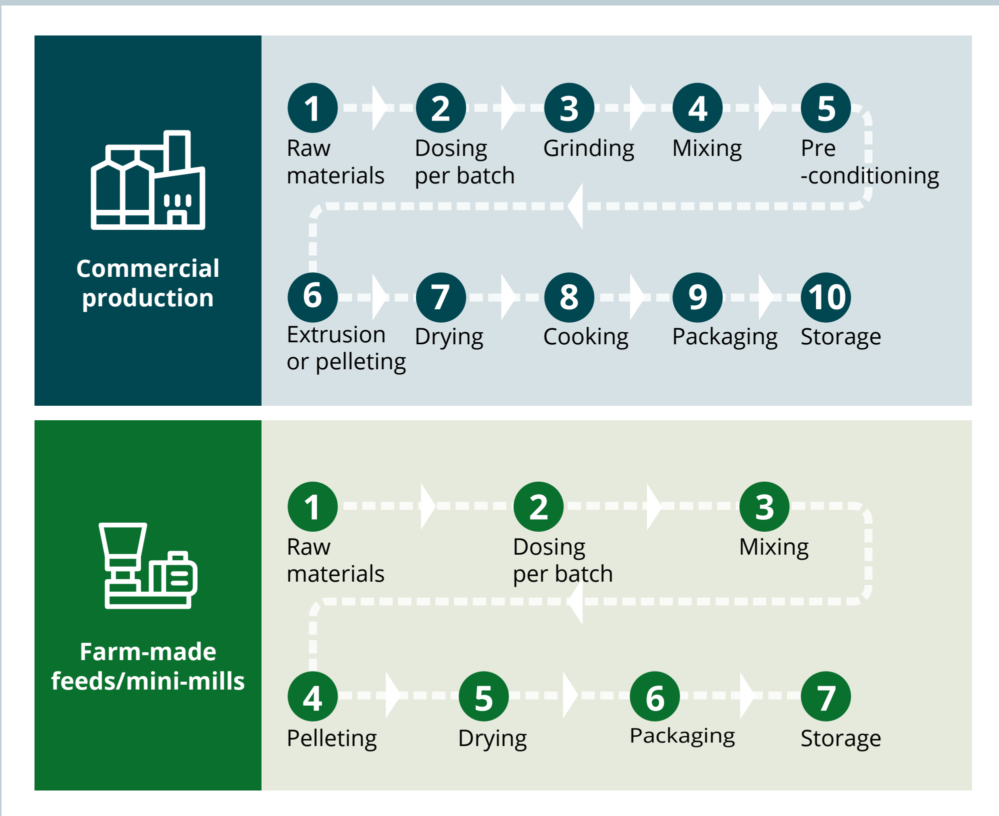


Figure 5 Steps for commercial production and farm-made (local) feed manufacturing processes

Table 3 Production steps for commercial feed manufacture

Production step	Requirements	Benefits	Drawbacks
Local raw material drying	Heat source, airflow, mixing	Shelf-stability (water activity <0.7).	Time and infrastructure cost – solar dryers can help when electricity is challenging.
Particle-size reduction	Mill – hammer or beater type	Size reduction increases digestibility and aids pellet formation. All particles should be <1/3 of die opening to prevent blocking.	Machine cost.
Mixing	Mechanical mixer depending on volume	Homogenous mix ensures all nutrients are equally available to all fish. Aids processing.	Machine cost or labour.
Preconditioning	Preconditioner	Heats and mixes water for starch gelatinisation. Required for large-scale pelleting and extrusion. Reduces some heat-labile antinutrients.	High cost and energy demand. Limited to commercial production.
Pelletisation	Pellet press	Forms feed into a shape that can be dried, transported and fed to fish. Lower cost and higher throughput than extrusion.	Limited starch gelatinisation, no floating feed potential, limited reduction in antinutrients.
Extrusion	Extruder	As above, but also increases heat and pressure. Increased pellet robustness. Further reduces heat-labile antinutrients. Can make floating feeds.	Expensive and technical.
Drying	Heat source, airflow, mixing	Stabilises pellets for storage up to 6 months (water activity <0.7).	Expensive and technical.
Cooling	Airflow	If feeds are packaged, they need to be close to ambient temperature to avoid sweating and mould.	Energy, cost and time. Not required if packaging is loose and breathable. If time and efficiency are not important, time will achieve cooking.

Farm-made feeds

Aquaculture feed can be made at a small scale, using relatively inexpensive equipment. By manufacturing feed on-farm the farmer is assured of the ingredients used and can control cost to a certain extent with their purchasing behaviour. Farm-made feeds are used where the cost of formulated feed is high and production intensity outstrips the nutrients provided by pond productivity or supplemental ingredients. The need for a complete feed necessitates a mixture of up to 20 ingredients, and the time, technical capacity and space required turns many farmers away from making their own feed (Romana-Eguia et al. 2013).

Centralised mini-mills

The technical constraints of farm-based feed production can be bypassed by centralising feed production in local mini-mills. By using relatively low-cost manufacturing equipment, mini-mills can reduce the capital investment required for industrial feed processing and increase buying power for feed materials compared to farm-made feeds (Booth 2017).

Pelletised feed

Investment in larger milling capacity is generally done on a larger and more centralised scale. Pelletisers are used to make terrestrial feed for pigs and chickens and the infrastructure is generally available.

Extruded feed

Extrusion utilises high pressure, temperature and moisture to form water-stable pellets with a high degree of starch gelatinisation and reduced antinutritional properties than cold-processed feeds. The benefit of extrusion for tilapia feeds is that buoyancy can be controlled, which aids feed management in more intensive systems, through accurate appetite assessment while surface feeding. Extrusion technology is considerably more expensive than pelletisation, both from an infrastructure cost and from increased energy expenditure. Nonetheless, high-intensity farming operations utilise extruded feeds because of their increased quality and the increased feeding control that they provide.

4.6 Understanding growth

Growth is influenced by genetics and other inputs, including nutrition, maturation, dissolved oxygen, temperature and other aspects of water quality. While genetic selection has resulted in strains of tilapia that enable faster production and improved efficiency under ideal conditions, these gains may not be realised in conditions where the environment limits production (Omasaki et al. 2017). For example, the genetically improved farmed tilapia GIFT strain can grow at up to twice the growth rate of red tilapia under ideal growth conditions; however, by inducing a temperature limitation on growth by rearing them at 22°C, the growth benefit is limited and potentially not detectable (Santos et al. 2013).

For a species that has a reportedly high tolerance to poor water quality and low nutritional requirements, there are many reports in the literature of very high feed conversion ratio (FCR) values (for example, 2.2–2.98 for <1 g fish (El-Sayed 2002), poor protein retention (8.23–11.7) and low survival (61–96%) (El-Sayed 2002)). Feed conversion rates appear to be poorer for satiety feeding than sub-satiety, both at the fry stage and for juveniles (da Silva et al. 2020; Cadorin et al. 2022). However, satiety feeding appears to consistently support optimal growth in intensive production conditions. While slight sub-satiety feeding did not decrease growth significantly for fry, fry survival was highest for satiety feeding, demonstrating the benefit of unrestricted nutrient supply. The downside of unrestricted feeding is that it can be self-limiting due to higher oxygen demand and ammonia output, deteriorating water quality (da Silva et al. 2020).

Tilapia are typically farmed in oxygen-limiting environments, where the cost of supplemental aeration trades off against its growth benefits (Yi and Lin 2001; Omasaki et al. 2017). While microalgae in ponds form a source of feed for filter-feeding tilapia, and produce oxygen during the day, it becomes a net consumer of oxygen overnight, often leading to growth-limiting oxygen conditions.

Feeding and digestive processes of tilapia cause a postprandial increase in oxygen uptake through specific dynamic action (SDA), so feeding rates and timing are integrally linked with oxygen consumption (Tran-Ngoc et al. 2016). Optimising growth per unit feed intake (FCR) is therefore of utmost importance for economical tilapia production, decreasing the direct feed cost as well as the indirect cost of aeration. The impact of oxygen on feed intake and growth may be size-dependent, with larger fish (200–270 g) in tanks optimising feed intake and growth at greater than 5.5 mg/L dissolved oxygen, whereas smaller fish (58–100 g) appear more tolerant of low oxygen, with optimal growth occurring at 3 mg/L dissolved oxygen and above (Tran-Duy et al. 2012). In contrast, tilapia between 23 g and 82 g have been reported to decrease growth by 15% when oxygen drops to 3.5 mg/L (Tran-Ngoc et al. 2016). These studies combined indicate that dissolved oxygen levels consistently below 4 mg/L may result in 15–20% loss in weight gain, while dissolved oxygen dipping to 2.5 mg/L may result in growth approximately 50% of maximum. In pond scenarios, oxygen fluctuates more widely and preventing dissolved oxygen from decreasing below 10% saturation at its minimum appears to be critical for optimal growth (Teichert-Coddington and Green 1993). However, aeration may also negatively affect growth if the aeration mechanism increases turbidity/total suspended solids (Yi and Lin 2001). Decreased growth due to low dissolved oxygen further results in poorer feed efficiency, meaning that more food is required per unit growth, further increasing oxygen demand per unit growth. While pond-reared tilapia experience high oxygen levels in the late afternoon, extremely low oxygen levels are common in the early morning (Diana and Lin 1998; Liti et al. 2005; Liti et al. 2006), which may account for part of the poor FCR and survival reported in many pond-reared tilapia studies.

Temperature increases growth, at least up to 30°C. This may not, however, result in maximum tilapia production, since warmer water is able to carry less oxygen, while also increasing metabolic demand for oxygen.

Protein levels in feed for tilapia increase growth. However, dietary protein is also the major contributor to oxygen demand through its energetically expensive metabolism (Tran-Ngoc et al. 2016). Tilapia diets containing 27.9% crude protein and 20.9% crude lipid can support the same growth as those containing 50% crude protein and 15.9% fat but with improved feed efficiency and approximately 15% lower oxygen consumption (Saravanan et al. 2012). Nutritional optima seem somewhat inconsistent with tilapia research, with early indications of 45% protein and 10% lipid being appropriate for fry, however, lipid levels exceeding 5% of the feed inhibit feed intake and growth for early developing tilapia (8–30 g) (Wangkahart et al. 2022).

Growth appears to be generally linear with tilapia size, making grams per day the predominant measure. High growth appears to be in the range of 3 g/day, with some extreme cases approaching 4 g/day. However, growth less than 1 g/day is common in low-intensity farming with little nutrient input or poor water quality. Identifying the limiting factors for growth will be key for farmers to reach their production goals and having the tools to understand their growth limitations will be key to optimising yield for their environment and input budget.

4.7 Recommendations

- Determine the characteristics of farm system type and production intensity in the different locations.
- Define the intent of farmers in the different geographies; for example, subsistence farming, farming to share/trade locally, farming to sell locally, and farming for transport to markets.
- Define the current versus desired production volume of farmers in order to determine the steps required to reach these aspirations.
- Optimise the use of locally available by-products as supplemental feed materials discrete from formulated and processed feeds.
- Evaluate locally available carbohydrate sources for optimising pond microbial productivity. Specifically, evaluate drying and milling size of carbohydrate sources for storage stability and availability for bacterial growth.
- Define the cost-benefit of different levels of feed supplementation with locally available agricultural by-products.
- Investigate the effect of processing on plant leaf materials.
- Develop BSFL and duckweed as feed materials or ingredients.
- Coordinate the import of chemicals, such as vitamin and mineral premixes, antioxidants, and binders needed for feed production.

5 Stimulating and sustaining enterprise growth

Live tilapia ready for sale in a fish shop, Timor-Leste.

A farmer checking water quality and plankton richness
using a Secchi disk in a tilapia pond, Timor–Leste.

5 Stimulating and sustaining enterprise growth

Tilapia farming was highlighted as a strategy for enhancing fish supply in Pacific island countries and Timor-Leste as a response to population growth and climate change nearly 15 years ago. However, progress during the past decade has been slow and uneven, despite apparent broad social, economic and market acceptance of tilapia (Pickering 2010). The development of specialised tilapia aquaculture businesses – at all scales across the micro, small and medium (MSME) spectrum and the value chain – is highly limited throughout the region. In Asia, the development of aquaculture, including tilapia aquaculture, involving entrepreneurs and investment in sustainable private businesses, rather than subsidised donor-funded initiatives, has been critical in reaching the scale needed, with domestic food supply, employment and livelihood benefits widely reported (Belton et al. 2018).

The challenges to development of business enterprises in the Pacific, such as small markets and limited investment and entrepreneurship support, have been widely reported (for example, ITC 2021), yet new and growing businesses represent the primary sources of job creation and innovative activity in an economy and tilapia aquaculture represents an opportunity that should be further explored. Present production of farmed tilapia among Pacific island countries is estimated at ~1,630 tonnes in 2022 (O'Meara et al. 2023), providing fairly limited scope for enterprise development. Yet the fish shortfalls projected to be in excess of 100,000 tonnes (Bell et al. 2009) should be providing significant opportunities for investment and enterprise development in the larger markets, particularly those facing greater fish deficits, notably PNG, Solomon Islands and Fiji.

The experience with private enterprise development in tilapia aquaculture to date though is extremely limited, and business-oriented ecosystems supporting enterprise development are similarly deficient in the Pacific. The expansion of inland tilapia farming in PNG has led to 60,000 households being involved, though most are subsistence farmers. Micro-businesses have emerged in some communities (largely satellite hatcheries), but other business development has been limited. Solomon Islands has progressed little with Mozambique tilapia and is awaiting an introduction of Nile tilapia to stimulate tilapia aquaculture growth. Timor-Leste has been actively encouraging private investment in small-scale hatcheries and traders to invest in building value chains between farmers and urban markets.

5.1 Subsistence, commercial farming and enterprises

Aquaculture strategies from Pacific island countries commonly emphasise the need to stimulate aquaculture through more commercially oriented growth and investment (Amos et al. 2014; FAO 2020). Fish for food security calculations analysed by Cleasby et al. (2014) for Solomon Islands concluded that homestead subsistence ponds are insufficient to meet fish demand, indicating that a combination of homestead and more commercial enterprises are required to supply future fish demand in the country. In PNG, while subsistence farming of tilapia has been widely promoted for homestead food production, entrepreneurs are also entering farming, and government is seeking commercial investment in farming and value chains (Nioney et al. 2023). In Timor-Leste, Pant et al. (2024) describes a gradual development of commercial farming among smallholders, generating tilapia for households, gifting or neighbours, and rural and urban markets. We conclude that a more commercial, entrepreneurial and business-oriented approach will be necessary to stimulate tilapia aquaculture at the scale required.

5.2 Markets

The market opportunity determines the investment and business opportunity. Per capita production of tilapia remains very small, suggesting the market has scope to grow. In PNG, the estimated 1,300 t/year of tilapia equates to 0.13 kg/person in a population of 10.3 million; in Timor-Leste the estimated 500 t/year equates to 0.4 kg/person for a population of 1.3 million, and less elsewhere. We conclude that a significant expansion in tilapia aquaculture will be essential to make a measurable contribution to food security at the scale envisaged by Bell et al. (2009), the assumptions of which appear to remain broadly valid.

Tilapia remains globally an affordable and accessible fish, with research to date suggesting the macro-level market situation is favourable for tilapia, with projected demand for fish in 11 Pacific island countries and territories, including PNG and Solomon Islands, beyond the capacity of coastal fisheries. The limited insights available suggest that tilapia is accepted in rural and urban markets in PNG, Solomon Islands (Cleasby et al. 2014) and Timor-Leste (Pant et al. 2023). More information is needed on affordability, but if tilapia is to grow at scale it will need to remain competitive in the market of marine fish and likely other animal protein sources, particularly chicken. Experiences in Fiji suggested that market promotion can be successful to create consumer awareness and open markets for farmers (Waqairatu-Waqainabete et al. 2022).

5.3 Investment case

Given the macro-scale fish demand, need for fish in Pacific diets, supply scenarios in PNG, Solomon Islands and Timor-Leste and generally unrealised opportunity for tilapia aquaculture to contribute to livelihoods and food, there appears to be a broad case for investing in tilapia aquaculture, with public and private sector playing a role.

The opportunity for private commercial enterprises in aquaculture can traditionally be found across the value chain, from farming enterprises of all scales, business providing inputs (hatcheries, feeds, and others), trading and marketing businesses, and other goods and services (such as training). In Asia, new digital disruptive companies are emerging in aquaculture, such the company e-fishery, which uses digital tools to create new efficiencies across the value chain (Novogratz 2023).

The size of the market and investment opportunity in PNG, Solomon Islands and Timor-Leste requires more research. However, in PNG and Timor-Leste, and other Pacific island countries, private tilapia aquaculture enterprises are emerging in farming (mainly small-scale), hatcheries (PNG, Timor-Leste and Fiji) and some marketing, though enterprises are small related to the size and organisation of the market. Solomon Islands remains an outlier with limited commercial development to date related to the delay in the introduction of GIFT. Digital technologies are also emerging in the Pacific (UNCTAD 2022), opening opportunities for value chain efficiencies, training and finance, though with limited application to aquaculture or wild fisheries to date. More promotion of the market and investment opportunity in tilapia aquaculture is required. Several investment funds are also available for aquaculture investment in the Asia-Pacific region that could be approached (such as Aqua-Spark and Asian Development Bank climate funds) and perhaps a Pacific regional aquaculture enterprise support and funding strategy could be further explored with a focus on catalysing more commercially oriented investment.

5.4 Smallholders and marginalised value chains

Smallholder farmers dominate the production systems throughout the Pacific, but suffer from inadequate access to inputs and markets and need special attention in any tilapia aquaculture commercialisation strategy. Investing in clustering and local business centres, and supporting the organisation of representative and inclusive farmer organisations are starting to be explored in Timor-Leste and PNG and can be further explored and supported. Waqairatu-Waqainabete et al. (2022) also noted the importance of creating 'market-oriented mindsets' among farmers and the organisation of value chains through aggregation of fish from smallholders to enable smallholder inclusion in the tilapia market opportunity. The importance of supporting promising entrepreneurs and providing an ecosystem of business support services in the Pacific is being recognised (ITC 2021) and tilapia aquaculture would likely benefit from a shift in donors and development partners towards a more entrepreneurship-oriented approach.

5.5 Governments and donor agencies

Governments and donor agencies can support the emergence of tilapia aquaculture enterprises in the region in various ways, including focusing policy efforts on tilapia as a high priority species, enabling policies (for example, import of ingredients, improved genetics) and marketing and public campaigns that are conducive to tilapia aquaculture. National aquaculture strategies could probably be refreshed with more focus on strategies for supporting leading entrepreneurs, commercial private sector growth, creating business support ecosystems, and enabling farmer organisations and private sector investors to identify investment opportunities. Donors may also consider strengthening capacities for incubation and acceleration of small businesses in the region, as well as seeking ways of encouraging investment by mitigating risks for business development within the region.

5.6 Recommendations

- Stimulate private enterprise investment, particularly for small- and medium-scale enterprises.
- Build the case for investment by understanding the marginalised supply chain issues, the limitations in available markets, and the socioeconomic drivers.
- Assess and implement ways to improve the ecosystem of support for aquaculture entrepreneurs and enterprises, such as business incubation, financing and creating supporting institutions.

6 Capacity building

Women play an important but often unrecognised role in inland aquaculture, PNG.

Producing tilapia provides an income opportunity, Timor-Leste.

6 Capacity building

Capacity building is a broad term encompassing the ability to adapt specialised skills and knowledge to local conditions to enhance development outcomes. Enhancing the knowledge, skills and abilities of individuals working in technical fields is an important part of primary industry research, including aquaculture. It involves providing training, resources and support to help people develop and expand their expertise in their respective areas, improving the longevity of research efforts by leaving a legacy of skilled people who can continue development instigated by the research investment.

Pacific island countries, with small populations, find it difficult to fill detailed technical roles to fit specific research and development needs. This is exacerbated by underdeveloped educational programs at both secondary and tertiary levels. For a small, nascent industry like aquaculture, reliable information can be hard to find, training programs are scarce, and it is difficult, if not impossible, to find on-the-job work experience. These difficulties make it especially hard for farmers commencing inland aquaculture in more remote areas. Similarly, government officers seeking to improve food security and income-generating opportunities from aquaculture, struggle to recruit appropriately qualified people.

Investing in capacity building is a priority for future research-for-development projects to address the barriers to tilapia aquaculture. This can improve the overall technical competency and efficiency of the workforce, leading to increased productivity, innovation and better outcomes for tilapia aquaculture. It will also help institutional professionals stay updated with the latest advancements, promote a culture of continuous learning and improvement and help build aquaculture networks.

ACIAR has a strong focus on capacity building, supported through its research-for-development projects and formal programs (fellowships to conduct postgraduate research, build leadership and research management skills, and empowerment of women as research leaders).

ACIAR has developed several programs of specific interest to addressing the barriers to aquaculture in PNG, Solomon Islands and Timor-Leste (ACIAR n.d.):

- Pacific Agriculture Scholarship and Support and Climate Resilience Program: supporting Pacific universities to foster thriving agricultural research education and supporting ACIAR's Pacific Scholars.
- Support to the Crawford Fund: to deliver training and links with Australian-based networks, masterclasses and an annual conference at Parliament House.
- Researchers in Agriculture for International Development network: supporting early-career Australian researchers to engage with agricultural research-for-development.
- ACIAR Alumni program: supporting a diverse and dynamic network of agricultural researchers throughout the Indo-Pacific.

To complement the existing programs, a deliberate focus on capacity building to empower aquaculture specialists, including tilapia, is needed to address one of the biggest barriers to developing tilapia aquaculture. This is needed at the farm level, regional level (for example, satellite hatcheries or aquaculture equipment supply centres), and institutional level (for example, National Fisheries Authority and National Department of Agriculture in PNG, Ministry of Fisheries and Marine Resources in Solomon Islands, and the Ministry of Agriculture and Fisheries in Timor-Leste).

Some of the elements which should be considered in designing a comprehensive capacity-building program for Pacific island countries and Timor-Leste are included below.

6.1 Programs and workshops

Internship programs

These programs would provide students (typically undergraduates or recent graduates), volunteers or prospective employees with the opportunity to work with government officers responsible for developing inland aquaculture, employed in the relevant institutions, in relevant countries. The primary goal of an internship is to provide practical learning opportunities and exposure to a professional work environment, fostering the intern's personal and professional development. Fundamentals of internship programs are detailed in **Appendix 2**.

Training workshops

These programs would provide intensive training sessions to enhance specific technical skills. They would cover topics like aquaculture nutrition, feed management, how to feed efficiently, tilapia hatchery management, production of single-sex fingerlings, and fingerling transport. More general programs on farmer engagement and training (train-the-trainer), water quality management, harvesting, processing, sale, and others, would also be beneficial. An ACIAR-supported masterclass program, run by the Crawford Fund, on tilapia hatchery technology, including broodstock management, single-sex fingerling production, transport and distribution of fingerlings and farmer training, would be a valuable initiative.

Certification programs

Capacity building through certification enables technical specialists to obtain recognised credentials in their fields. The most important examples for tilapia aquaculture for Pacific island countries include certification in producing single-sex tilapia fingerlings and certification in producing locally made tilapia feeds.

Mentorship programs

Two programs are recommended: the first would pair experienced lead farmers with less experienced farmers, and the second would pair technical professionals with emerging professionals. International professionals could act as mentors where appropriate. Mentorship programs offer personalised support and advice to help individuals grow and develop their technical expertise.

Networks/associations

Farmer associations might offer another avenue for enhancing exchange of knowledge and experience between farmers within and between countries. Fiji has made some progress in building a tilapia farmers association that includes capacity building within its remit. A Pacific islands farmers organisation network also exists but it is unclear how much involvement or interest there is in aquaculture. A Pacific islands/Timor-Leste network for tilapia culture and agribusiness opportunities, perhaps building with existing organisations where they exist, has the potential to assist aquaculture development in the region and could be further explored.

Professional conferences and seminars

Supporting emerging aquaculture specialists from Pacific island countries to attend conferences and seminars provides technical specialists with opportunities to network, learn about emerging trends, and gain insights from industry experts. Such events often include workshops and presentations to enhance specific technical skills.

Online learning platforms

With the rise of e-learning, various platforms provide technical specialists with online courses and resources to develop their skills at their own pace. At its most elaborate, this can take the form of specific training platforms that facilitate lectures and other training material, including interactive online spaces and training packages such as those made in H5P (a free platform for creating online training). Lower intensity options include online video streaming of training materials or interactive walkthroughs. One of the key limitations of online delivery is ongoing servicing, updating and hosting arrangements inherent with technology that require ongoing commitment and funding.

6.2 Legacy capacity tools

Capacity tools that continue to be useful post-project have an ongoing effect that can make investment particularly fruitful in the long-term. Training individuals can be productive as ongoing resources if they become trainers, but materials that continue post-project can continue to train incidentally irrespective of investment from individuals. Tools like manuals that are physically printed can be useful in this regard, as can posters that are visible and useful as ongoing reference materials.

The specifics of capacity-building programs may vary depending on consultation with tilapia farmers in the PNG, Solomon Islands, Timor-Leste and other countries in the region. The key is to provide opportunities for farmers to access knowledge and learning opportunities and to support technical specialists to continuously learn and grow professionally. The potential for efficient use of digital platforms and tools remains to be explored.

6.3 Recommendations

- Consult with Pacific island countries to identify existing capacity and prioritise capacity-building needs. Design capacity-building programs around the needs of the tilapia farming sector and existing networks, including government and private.
- Internship programs, training workshops and online learning platforms are the initial priority.
- Examine the role for regional networks to help address some of the scale issues.

7 Overall recommendations

School children at the Goroka Show participate in the Fish for Schools program, PNG.

7 Overall recommendations

These recommendations are collated from the chapters (including **Appendix 1**) of this report. All recommendations are then recrafted into a framework based on outcomes, implementation activities, interdependencies and outputs.

7.1 Summary of recommendations

Socioeconomic impacts affecting tilapia aquaculture

- Update projections about the fish supply shortfall for the Pacific, including better insights on socioeconomic impacts (for example, income, nutrition and gender).
- Examine the role of tilapia for fish supply and identify socioeconomic characteristics that might affect potential growth.

Fingerling production

- Improve genetic management of tilapia, including the importation of better genetics (such as GIFT) into Solomon Islands and broodstock management in other countries.
- Increase adoption of single-sex production of fingerlings by increasing access to essential chemicals and equipment.
- Assess viability of a central distribution centre ('regional hub') for genetically improved tilapia broodstock and/or fry among Pacific ACP countries for biosecurity and to achieve economies of scale.
- Create incentives and strategies for the private sector to invest in tilapia hatcheries, including small-scale satellite hatcheries.
- Assess the satellite hatchery approach in PNG and Timor-Leste to explore the potential for wider application, including use of satellite hatcheries as local 'business centres' for supporting local entrepreneurs and farmers.
- Focus on capacity building and training.

Feeds and feeding

- Determine the characteristics of farm system type and production intensity in the different locations.
- Define the intent of farmers in the different geographies. For example, subsistence farming, farming to share/trade locally, farming to sell locally, and farming for transport to markets.
- Define the current versus desired production volume of farmers to determine the steps required to reach these aspirations.
- Optimise the use of locally available by-products as supplemental feed materials discrete from formulated and processed feeds.
- Evaluate locally available carbohydrate sources for optimising pond microbial productivity. Specifically, evaluate drying and milling

size of carbohydrate sources for storage stability and availability for bacterial growth.
- Define the cost-benefit of different levels of feed supplementation with locally available agricultural by-products.
- Investigate the effect of processing on plant leaf materials.
- Develop BSFL and duckweed as feed materials or ingredients.
- Coordinate the import of chemicals, such as vitamin and mineral premixes, antioxidants and binders needed for feed production.

Enterprise growth

- Stimulate private enterprise investment, particularly for small- and medium-scale enterprises.
- Build the case for investment by understanding the marginalised supply chain issues, the limitations in available markets, and the socioeconomic drivers.

Capacity building

- Consult with Pacific island countries to identify existing capacity and prioritise needs. Design capacity-building programs around the needs of the tilapia farming sector and existing networks, including government and private.
- Internship programs, training workshops and online learning platforms are the initial priority.
- Examine the role for regional networks to help address some of the scale issues.

Black soldier fly larvae

- Examine occurrence of BSF in areas where tilapia farming occurs and if populations are sufficient to establish BSF culture and restart after production interruptions.
- Examine whether suitable conditions exist for BSF culture.
- Determine if sufficient, available organic material (for example, waste) exists to culture enough BSFL for the amount of tilapia to be cultured (how many flies are needed to produce enough larvae for fish and how much waste/nutrients are needed to produce those flies).
- Investigate feasibility of BSFL for subsistence and community-scale tilapia farming in remote areas.
- Determine the type and scale of BSFL culture facilities that are needed.
- Determine if BSFL can be used as a wet feed.
- Determine if BSFL can be dried and used as an ingredient in farm-made feeds.
- Evaluate if BSFL can be 'self-feeding' (when BSFL transition to pre-pupa (day 21–27), they move away from their feed source).

7.2 Recommendations framework

The recommendations framework recrafts the recommendations as desired outcomes, activities, interdependencies and outputs, shown in **Table 4**.

Table 4 Recommendations framework

Desired outcome	Activities	Interdependencies (parallel activities, synergies, gaps)	Outputs
The tilapia market size and potential for tilapia to contribute to projected fish shortfall is understood. The role for tilapia and socioeconomic drivers is understood.	• Market research to assess tilapia market size and value chain development opportunities. • Update projections about the fish supply shortfall for the Pacific, including better insights on socioeconomic impacts of trends and actions (for example, on income, nutrition and gender). • Examine the role of tilapia for fish supply and identify socioeconomic characteristics that might affect potential growth.	• Studies on the impacts of climate change on capture fisheries and aquaculture in Pacific island countries. • Global and regional fisheries and aquaculture statistics compiled and published. • Studies of socioeconomic insights for Pacific island countries to inform drivers for tilapia aquaculture, food security, market development and gender.	• Market and business case reports. • Published reports.
High quality, single-sex fingerlings are consistently available.	• Improve genetic management of tilapia, including the importation of better genetics (such as GIFT) into Solomon Islands and broodstock management in other countries. • Increase adoption of single-sex production of fingerlings by increasing access to essential chemicals and equipment. • Assess viability of a central distribution centre ('regional hub') for genetically improved tilapia broodstock and/or fry among Pacific ACP countries for biosecurity and to achieve economies of scale. • Create incentives and strategies for the private sector to invest in tilapia hatcheries, including small-scale satellite hatcheries. • Assess the satellite hatchery approach in PNG and Timor-Leste to explore the potential for wider application, including use of satellite hatcheries as local 'business centres' for supporting local entrepreneurs and farmers. • Focus on capacity building and training.	• Improvements in genetic breeding programs. • Improvements in hatchery technology, especially for small-scale tilapia farms. • Interest/willingness to champion regional centres or networks. • Importation of genetically improved tilapia into Solomon Islands. • Coordinated import mechanisms for essential chemicals (for example, vitamin/mineral premixes). • Capacity building.	• Availability of better broodstock. • Published hatchery technology (for hatchery operators). • Regional network. • Increased investment from private sector. • Link with existing ACIAR projects (for example, FIS-2018-154). • New ACIAR project.

Table 4 Recommendations framework *(continued)*

Desired outcome	Activities	Interdependencies (parallel activities, synergies, gaps)	Outputs
Improved cost-effective feeds for different types of tilapia farms.	• Determine the characteristics of farm system type, production intensity and profitability in the different locations. • Define the intent of farmers in the different geographies. For example, subsistence farming, farming to share/trade locally, farming to sell locally, and farming for transport to markets. • Define the current versus desired production volume of farmers in order to determine the steps required to reach these aspirations. • Optimise the use of locally available by-products as supplemental feed materials discrete from formulated and processed feeds. • Evaluate locally available carbohydrate sources for optimising pond microbial productivity. Specifically, evaluate drying and milling size of carbohydrate sources for storage stability and availability for bacterial growth. • Define the cost-benefit of different levels of feed supplementation with locally available agricultural by-products. • Investigate the effect of processing on plant leaf materials. • Develop BSFL and duckweed as feed materials or ingredients. • Coordinate the import of chemicals, such as vitamin and mineral premixes, antioxidants, and binders needed for feed production.	• Comprehensive surveys of potential and existing tilapia farms and farmers. • Recent survey of potential locally available feed ingredients. • Studies to determine potential role for carbohydrate sources to accelerate pond productivity. • Coordinated import mechanisms for essential chemicals (for example, vitamin/mineral premixes).	• Link with existing ACIAR projects (for example, FIS-2018-154). • New ACIAR project.

Table 4 Recommendations framework *(continued)*

Desired outcome	Activities	Interdependencies (parallel activities, synergies, gaps)	Outputs
Stimulating enterprise and entrepreneurs to invest and grow tilapia businesses.	• Stimulate private enterprise investment, particularly for small- and medium-scale enterprises. • Build the case for investment by understanding the marginalised supply chain issues, the limitations in available markets, and the socioeconomic drivers. • Support to local entrepreneurs for satellite hatcheries and local clusters that support local farming and value chain activities. • Support to develop/professionalise farmer associations.	• Studies and market research to examine barriers to investment.	• Published reports and increased awareness.
Capacity building and training.	• Consult with Pacific island countries to identify existing capacity and prioritise needs. • Design capacity-building programs around the needs of the tilapia farming sector and existing networks, including government and private. • Internship programs, training workshops and online learning platforms are the initial priority. • Examine the role for regional networks to help address some of the scale issues.	• ACIAR capacity development framework. • Crawford Fund programs (for example, masterclasses and other projects). • University and other education programs. • National government programs (for example, National Fisheries Authority Fish for Prisons and Fish for School programs in PNG).	• Project outputs. • Published reports and increased awareness.
Determine if culture of BSFL as a feed for tilapia is suitable for remote areas in PNG, Solomon Islands and Timor-Leste.	• Examine where BSF occurs in relation to tilapia farms. • Examine whether suitable conditions exist for BSF culture. • Examine whether sufficient organic material (for example, waste) is available for BSF culture. • Examine feasibility of BSF culture in remote areas. • Determine if BSFL can be used as a wet feed.	• Studies to determine the potential for BSFL as feed ingredient, particularly in remote areas for subsistence and community farms.	• Small Research Activity to evaluate potential for BSFL.

8 Conclusion

A public-private partnership model GIFT hatchery with hapa breeding and incubation facility in Colucau, Timor–Leste.

Fishing for tilapia in an aquaculture pond, Solomon Islands.

8 Conclusion

Fish make up the majority of animal-derived protein for people living in Pacific island countries but supply is expected to become increasingly unreliable because of factors like overfishing and climate change. Inland communities already have limited access to protein and the region is facing diet-related challenges of undernutrition, micronutrient deficiencies and over-nutrition. The forecast reduction in fish supply will exacerbate malnutrition issues, particularly juvenile stunting and adult obesity.

Fish production, with low technology needs and low-cost inputs, such as tilapia, can play a critical role in food security and nutritional health of isolated and poor inland communities.

This review examined the challenges to increasing tilapia production in PNG, Timor-Leste and Solomon Islands, with suggested pathways to address these challenges. While each of these countries is unique, there are similarities in the challenges and potential solutions. Many other Pacific island countries face similar challenges and, hopefully, the potential solutions will also be relevant there.

There are 4 categories of challenges that combine to constrain the growth of tilapia aquaculture:

1. Consistent availability of high-quality, single-sex fingerlings.
2. Availability of cost-effective feeds and feeding solutions.
3. Stimulating and sustaining economically viable enterprises.
4. Capacity building and training to meet the needs of farmers, associated businesses, entrepreneurs, extension officers, policymakers and educators.

The small scale and remote geography of many Pacific island countries make addressing these challenges particularly difficult.

Hatchery production of high-quality fingerlings is crucial for any successful finfish aquaculture. For tilapia in Pacific island countries, the introduction of genetically improved Nile tilapia strains is critical where not currently available (for example, Solomon Islands), and broodstock must be carefully managed to maintain genetic quality fundamental everywhere. Access to essential chemicals, such as the synthetic hormone 17α-methyltestosterone, is needed, as is private investment in hatcheries, including satellite hatcheries, and distribution centres.

Cost-effective feeds and feeding solutions will depend on the type of tilapia farms. For subsistence and community farms, natural productivity enhanced by fertilisation, supplemented with single ingredients is likely to be the feed pathway. The potential role of insect meal, such as BSFL, possibly in conjunction with duckweed production in grow-out ponds, should be explored. For small-scale commercial farms, manufactured pellets, potentially made in-country using at least some local feed ingredients should be explored. There is a strong case for continuing subsidised import of commercially extruded tilapia feeds. This will fast-track industry development, help identify production capacity of different types of farms, and help the upskilling of tilapia farmers.

Stimulating private enterprise investment, particularly for small- and medium-scale enterprises and farming entrepreneurs, will be fundamental to ongoing growth of tilapia farming in Pacific island countries. Building the case for investment will require an understanding of the marginalised supply chain issues, the limitations in available markets, and the socioeconomic drivers for production in Pacific island countries.

Perhaps the common feature of all challenges for tilapia aquaculture in Pacific island countries is the need for capacity building and training. Capacity building is a broad term encompassing the ability to adapt specialised skills and knowledge to local conditions to enhance development outcomes. Enhancing the knowledge, skills and abilities of individuals working in aquaculture, including farmers, entrepreneurs, managers and employees in associated business, extension officers, policymakers and educators, requires appropriate training, resources and support. For capacity building and to address all the challenges described in this review, there is a role for government support and regional coordination.

Appendices

Photo: Jes Summut, University of NSW

Community outreach, such as demonstrations and field visits, promote fish farming as a means to producing protein, PNG.

Appendices

Appendix 1: Black soldier fly larvae as a potential feed for tilapia

Does black soldier fly larvae (BSFL) have potential as a feed or feed ingredient for tilapia aquaculture in PNG, Solomon Islands and Timor-Leste, and other Pacific island countries?

A number of insect species have been trialled as feeds or feed ingredients for aquaculture species but the black soldier fly (BSF), *Hermetia illucens*, Order Diptera, Family Stratiomyidaea, has attracted the most interest due to the ability of the larvae to efficiently convert waste from a range of organic material, including waste food materials, animal offal, kitchen waste and manure, into protein-rich feeds or feed ingredients (Mohan et al. 2022; Wang and Shelomi 2017).

The characteristics of the BSF are compelling. The adult fly consumes nothing except water, does not bite, sting or even approach humans, and is not a vector for any specific diseases (Wang and Shelomi 2017). BSFL do not accumulate pesticides, mycotoxins or most heavy metals (Shelomi 2020). The species occurs worldwide in tropical and temperate regions. Producing BSFL is cheap and doesn't require specialised skills, both of which are attractive features for farmers in developing economies. The lifecycle of the BSF is shown at **Figure 6**.

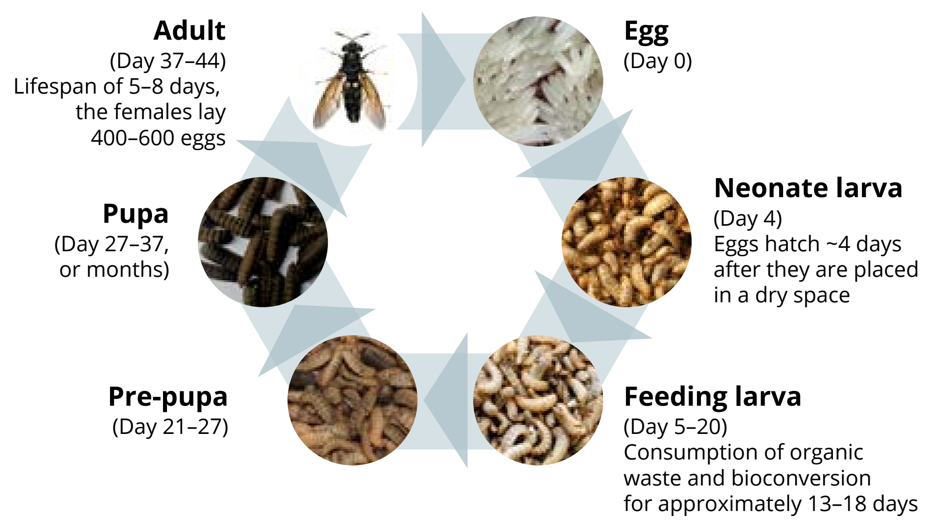


Figure 6 The lifecycle of black soldier fly
Source: Yu Lin Li 2021

Black soldier fly occurs in many Pacific island countries, including PNG, Solomon Islands, Timor-Leste, Vanuatu, Samoa, Cook Islands, Palau, Marshall Islands, Kiribati and the Federated States of Micronesia, but its presence in other Pacific island countries, including Fiji, Tonga, Nauru and Tuvalu is unknown (Shelomi 2020). Its presence on Timor-Leste is also unknown. In the Pacific generally, BSF has been identified as a potential solution for many of the significant, region-specific waste management issues (Shelomi 2020). Frass, the remains from BSFL, which comprise faeces, shed exoskeleton and substrate residue, is highly prized as an organic fertiliser with potential as an alternative to commercial fertilisers (Beesigamukama et al. 2020).

In recognition of the potential, ACIAR has invested in a number of projects to help evaluate the potential for insect-based (including BSFL) animal feed and develop insect-based agrifood systems (ACIAR 2022).

The nutritional constituents of BSFL, particularly the relatively high-protein content and attractive amino acid profiles, highly digestible lipids, absence of antinutritional factors and evidence of positive effects on immune stimulation, have excited considerable interest in the use of BSFL as a feed for aquaculture species (Webster et al. 2016). For a thorough review of the nutritional composition of BSFL and published research results for BSFL as a feed for aquaculture species, see Mohan et al. (2022). Mohan et al. reports approximately 130 research papers that were 'indexed in Pubmed, Scopus, Web of Science, and databases with the keywords "Black soldier fly", "Larvae meal", "food sources", and "Aquaculture"'.

Three components of BSFL have been tested in feeds for tilapia: BSFL meal (a protein-rich ingredient, the most obvious component with potential), BSFL oil and frass. The following summary has been distilled from published research on using these components as feed for tilapia (*Oreochromis* spp, mostly *O. niloticus*):

1. Replacing fishmeal with BSFL meal improved growth response, feed conversion ratio, and feed efficiency in juveniles. In another study, replacing 100% of fishmeal with BSFL meal significantly improved growth without adverse effects (Muin et al. 2017; Aini et al. 2018 in Mohan et al. 2022; Tippayadara et al. 2021 in Mohan et al. 2022).
2. Replacement of 50% fish oil in diets for juvenile hybrid tilapia was highly digestible and did not alter the haematological parameters (Bakar et al. 2021 in Mohan et al. 2022).
3. Frass from the BSFL meal industry, tested at 0%, 5%, 10%, 20% and 30% as a partial replacement for feed did not have any negative effects on the blood haematology and serum profile of tilapia (Yildirim-Aksoy et al. 2020 in Mohan et al. 2022).
4. Further studies were recommended to determine the impact of BSFL meal on muscle proximate composition, fatty acids and amino acids levels, and on the immune response of tilapia (Mohan et al. 2022).

Despite the potential of BSFL, its industrial upscaling has been limited by the cost of production compared to commonly available raw materials with similar nutrient profiles. However, in an environment where protein is relatively scarce, the ability of BSFL to concentrate protein from waste products into a form that can be directly consumed by fish may make it attractive for small-scale remote tilapia farming.

In summary, BSFL is present in PNG, Timor-Leste and Solomon Islands is relatively easy to cultivate, has few undesirable characteristics, might help with waste management and is a good feed for tilapia. BSFL could be a solution to the difficulty accessing cost-effective feeds and protein-rich feed ingredients, especially in remote areas in PNG, Solomon Islands, Timor-Leste and other Pacific island countries.

Recommendations

- Examine occurrence of BSF in areas where tilapia farming occurs and if populations are sufficient to establish BSF culture and restart after production interruptions.
- Examine whether conditions exist for BSF culture.
- Determine if sufficient, available organic material (for example, waste) exists to culture enough BSFL for the amount of tilapia to be cultured (how many flies are needed to produce enough larvae for fish and how much waste/nutrients are needed to produce those flies).
- Investigate feasibility of BSFL for subsistence and community-scale tilapia farming in remote areas.
- Determine the type and scale of BSFL culture facilities that are needed.
- Determine if BSFL can be used as a wet feed.
- Determine if BSFL can be dried and used as an ingredient in farm-made feeds.
- Evaluation if BSFL can be ‘self-feeding’ (when BSFL transition to pre-pupa (day 21–27), they move away from their feed source).
- Determine if the culture of BSFL as a feed for tilapia is suitable for remote areas in PNG, Solomon Islands and Timor-Leste.

Appendix 2: Details of internship programs

To support capacity building in tilapia production and research in Pacific island countries, internships are one element to consider as part of a broader capacity-building program.

Internship programs provide students (typically undergraduates or recent graduates), volunteers or prospective staff members with the opportunity to work with the government officers responsible for developing inland aquaculture, employed in the relevant institutions, in relevant countries. The primary goal of an internship is to provide practical learning opportunities and exposure to a professional work environment, fostering the intern's personal and professional development.

Fundamentals of internship programs include:

- **Application and selection:** Interested candidates typically apply for internships through an application process that may involve submitting a resume, cover letter, and possibly completing an interview. Candidates are selected based on their qualifications, skills, and potential fit within the organisation.
- **Duration:** Internships could range in duration from a few weeks to several months, depending on the program and the needs of the government agency. Some internships are full-time, while others may be part-time or offer flexible working hours to accommodate students' schedules.
- **Learning objectives:** Before starting the internship, employers and interns typically establish specific learning objectives and goals. These objectives can include gaining hands-on experience, developing specific skills, learning about the industry, or understanding the company's operations.
- **Supervision and guidance:** Interns usually work under the supervision of a mentor or supervisor who provides guidance, assigns tasks, and offers feedback throughout the internship. The mentor helps interns navigate their role, offers advice, and helps them learn and grow professionally.
- **Responsibilities and projects:** Interns are often assigned a variety of tasks and projects related to their field of interest. This can include research, data analysis, contributing to ongoing projects, assisting with administrative tasks, or working on specific assignments to meet organisational goals.
- **Networking and professional development:** Internship programs offer opportunities for interns to network with professionals in their field, attend company events or meetings, and participate in various training sessions or workshops. These experiences can enhance their knowledge, expand their professional network and provide insights into potential career paths.
- **Evaluation and feedback:** At the end of the internship, interns often receive an evaluation that considers their performance, achievements and areas for improvement. Feedback is provided to help interns reflect on their experience and potentially apply the lessons learned to future endeavours.

It is important to note that specific internship programs may have additional or different elements, depending on the organisation. There is an important research consideration to improve the specificity of internship programs for Pacific island countries. Some researchable questions include:

- What is the career trajectory of interns?
- Do interns increase the ability of government to engage with tilapia farmers?
- What are the best recruitment processes, and most appropriate programs to develop and deliver learning opportunities for interns?

References

ACIAR (n.d.) Capacity Building Knowledge Hub (web page), Australian Centre for International Agricultural Research, **www.aciar.gov.au/capacity-building/capacity-building-knowledge-hub**, accessed 28 October 2024.

ACIAR (2022) 'Australia invests in insect research centre' (media release), Australian Centre for International Agricultural Research, **www.aciar.gov.au/media-search/news/australia-invests-insect-research-centre**, accessed 28 October 2024.

Acosta BO and Gupta MV (2010) 'The genetic improvement of farmed tilapias project: Impact and lessons learned' in Silva SS and Davy FB (eds), *Success Stories in Asian Aquaculture* (149–171), Dordrecht, Springer Netherlands.

Aini N, Nugroho RA and Hariani N (2018) 'Growth and Survival Evaluation of *Oreochromis Sp* fed *Hermetia illucens* Larva and Manihot esculenta leaves Meal', *Biosaintifika: Journal of Biology & Biology Education*, 10(3):565–573, doi:**10.15294/biosaintifika.v10i3.15278**.

Almazan AM (1995) 'Antinutritional factors in sweetpotato greens', *Journal of food composition and analysis*, 8:363–368.

Asche F and Zhang D (2013) 'Testing structural changes in the U.S. whitefish import market: an inverse demand system approach', *Agricultural and Resource Economics Review,* 42(3):453–470.

Avnimelech Y (1999) 'Carbon/nitrogen ratio as a control element in aquaculture systems', *Aquaculture*, 176:227–235.

Avnimelech Y (2007) 'Feeding with microbial flocs by tilapia in minimal discharge bio-flocs technology ponds', *Aquaculture*, 264:140–147.

Bakar N-HA, Razak SA, Taufek NM, Alias Z (2021) 'Evaluation of black soldier fly (*Hermetia illucens*) prepupae oil as meal supplementation in diets for red hybrid tilapia (*Oreochromis* sp.)', *International Journal of Tropical Insect*, Science 1–10.

Beesigamukama D, Mochoge B, Korir NK, Fiaboe KKM, Nakimbugwe D, Khamis FM, Subramanian S, Dubois T, Musyoka MW, Ekesi S, Kelemu S and Tanga SM (2020) 'Exploring Black Soldier Fly Frass as Novel Fertilizer for Improved Growth, Yield, and Nitrogen Use Efficiency of Maize Under Field Conditions', *Frontiers in Plant Science*, 11, **doi:10.3389/fpls.2020.574592**.

Bell JD, Johnson JE and Hobday AJ (eds) (2011) *Vulnerability of tropical Pacific fisheries and aquaculture to climate change*, Secretariat of the Pacific Community, Noumea, New Caledonia.

Bell JD, Kronen M, Vunisea A, Nash WJ, Keeble G, Demmke A, Pontifex S and Andréfouët S (2009) 'Planning the use of fish for food security in the Pacific', *Marine Policy*, 33:64–76.

Belton B, Bush SR and Little DC (2018) 'Not just for the wealthy: Rethinking farmed fish consumption in the Global South', *Global Food Security*, 16:85–92, **doi.org/10.1016/j.gfs.2017.10.005**.

Bogard JR, Andrew NL, Farrell P, Herrero M, Sharp MK and Tutuo J (2021) 'A typology of food environments in the Pacific region and their relationship to diet quality in Solomon Islands', *Foods*, 10:2592.

Bonis-Profumo G, Gomes S, Tilman E, Pereira A, Soares de Jesus LA, Faria Simões NDD, Pires NM, Pereira M, Teoh SJ, Bhujel RC, Klumplyan K, Bogard JR and Pant J (2024) *The Fish in School Meals pilot report,* WorldFish, Project report 2024-19, Penang, Malaysia, **https://digitalarchive.worldfishcenter.org/server/api/core/bitstreams/6f314d9e-d98a-4d2c-bfdf-5a47267db24d/content**.

Booth MA (2017) 'Production of aquafeed for fish farmers in Papua New Guinea: challenges and opportunities', in Glatz P (ed) *Local feed resources for pig, poultry and fish production in Papua New Guinea*, Australian Centre for International Agricultural Research.

Boyd CE and Tucker CS (2012) 'Pond aquaculture water quality management', *Springer Science & Business Media*.

Byrd KA, Shieh J, Mork S, Pincus L, O'Meara L, Atkins M and Thilsted SH (2022) 'Fish and fish-based products for nutrition and health in the first 1000 days: a systematic review of the evidence from low and middle-income countries', *Advances in Nutrition*, 13:2458–2487.

Cadorin DI, da Silva MF, Masagounder K and Fracalossi DM (2022) 'Interaction of feeding frequency and feeding rate on growth, nutrient utilization, and plasma metabolites of juvenile genetically improved farmed Nile tilapia, *Oreochromis niloticus*' *Journal of the World Aquaculture Society*, 53:500–515.

Chaston Radway K, Manley M, Mangubhai S, Sokowaqanilotu E, Lalavanua W, Bogiva A, Caginitoba A, Delai T, Draniatu M, Dulunaqio S, Fox M, Koroiwaqa I, Naisilisili W, Rabukawaqa A, Ravonoloa K and Veibi T (2016) *Impact of Tropical Cyclone Winston on Fisheries-Dependent Communities in Fiji*, Report No. 03/16, Wildlife Conservation Society, Suva, Fiji.

Chevanan N, Muthukumarappan K and Rosentrater KA (2009) 'Extrusion studies of aquaculture feed using distillers dried grains with solubles and whey', *Food and Bioprocess Technology,* 2:177–185.

Cleasby N et al. (2014) 'The socio-economic context for improving food security through land based aquaculture in Solomon Islands: a peri-urban case study', *Marine Policy*, 45:89–97, **doi.org/10.1016/j.marpol.2013.11.015**.

Conte L, Sonoda D, Shirota R and Cyrino JEP (2008) 'Productivity and economics of Nile Tilapia *Oreochromis niloticus* cage culture in South-East Brazil', *Journal of Applied Aquaculture*, 20:18–37.

da Silva MA, de Alvarenga ÉR, Costa FFBd, Turra EM, Alves GFdO, Manduca LG, de Sales SCM, Leite NR, Bezerra VM and Moraes SGdS (2020) 'Feeding management strategies to optimize the use of suspended feed for Nile tilapia (*Oreochromis niloticus*) cultivated in bioflocs', *Aquaculture Research*, 51:605–615.

David LH, Pinho SM, Romera DM, Campos DW, Franchini AC and Garcia F (2022) 'Tilapia farming based on periphyton as a natural food source', *Aquaculture*, 547(737544).

Diana JS (2012) 'Some principles of pond fertilization for Nile tilapia using organic and inorganic inputs', *Aquaculture pond fertilization: impacts of nutrient input on production*, 163–177.

Diana JS and Lin CK (1998) 'The effects of fertilization and water management on growth and production of Nile tilapia in deep ponds during the dry season', *Journal of the World Aquaculture Society*, 29:405–413.

Diana JS, Lin CK and Schneeberger PJ (1991) 'Relationships among nutrient inputs, water nutrient concentrations, primary production, and yield of *Oreochromis niloticus* in ponds', *Aquaculture*, 92:323–341.

Diana JS, Lin CK and Yi Y (1996) 'Timing of supplemental feeding for tilapia production', *Journal of the world aquaculture society*, 27:410–419.

Eknath AE and Hulata G (2009) 'Use and exchange of genetic resources of Nile tilapia (*Oreochromis niloticus*)', *Reviews in Aquaculture*, 1:197–213, **https://doi.org/10.1111/j.1753-5131.2009.01017.x**.

Eldredge LG (1994) *Perspectives in aquatic exotic species management in the Pacific Islands Volume 1, Introductions of commercially significant aquatic organisms to the Pacific islands, March 1994, 127,* Inshore Fisheries Research Project Technical Document No 7.

El-Sayed, A-FM (2019) *Tilapia Culture: Second Edition*, Academic Press, San Diego, US.

El-Sayed A-FM (2002) 'Effects of stocking density and feeding levels on growth and feed efficiency of Nile tilapia (*Oreochromis niloticus L.*) fry', *Aquaculture Research*, 33:621–626.

El-Sayed A-FM and Fitzsimmons K (2023) 'From Africa to the world—The journey of Nile tilapia', *Reviews in Aquaculture*, 15(Suppl. 1):6–21, doi:**10.1111/raq.12738**.

FAO (2024) The State of the World Fisheries and Aquaculture 2024 (website), Food and Agriculture Organization of the United Nations, **openknowledge.fao.org/items/06690fd0-d133-424c-9673-1849e414543d**, accessed on 2 February 2025.

Fiji Ministry of Fisheries and Forestry (2024) *Fiji Aquaculture Development Plan 2024–2028*, Ministry of Fisheries and Forestry, Fiji.

Fitzsimmons K (2000) 'Tilapia: The Most Important Aquaculture Species of the 21st Century', proceeding from the *Fifth International Symposium on Tilapia Aquaculture*, Rio de Janeiro, Rio de Janeiro, Brazil.

Fitzsimmons K, Martines-Garcia R and Ganzalez-Alanis P (2011) 'Why is tilapia becoming the most important food fish on the planet?' in Liping L and Fitzsimmons K (eds) *Better science, better fish, better life*, proceedings of the *Ninth International Symposium on Tilapia in Aquaculture*, Shanghai Ocean University, Shanghai, China 22–24 April 2011.

Foo Yu Lin and Audrey Li (2021) A primer on the Black Soldier Fly Market in Asia [web page], Mana Impact, **www.manaimpact.com/post/a-primer-on-the-black-soldier-fly-market-in-asia**.

Francis G, Makkar HP and Becker K (2001) 'Antinutritional factors present in plant-derived alternate fish feed ingredients and their effects in fish', *Aquaculture*, 199:197–227.

Friedlander AM and Gaymer CF (2021) 'Progress, opportunities and challenges for marine conservation in the Pacific islands', *Aquatic Conservation: Marine and Freshwater Ecosystems*, 31:221–231.

Garcia F, Romera D, Sousa N, Paiva-Ramos I and Onaka E (2016) 'The potential of periphyton-based cage culture of Nile tilapia in a Brazilian reservoir', *Aquaculture*, 464:229–235.

Golden CD, Koehn JZ, Shepon A, Passarelli S, Free CM, Viana DF, Matthey H, Eurich JG, Gephart JA and Fluet-Chouinard E (2021) 'Aquatic foods to nourish nations', *Nature*, 598:315–320.

García-Gómez R, Bermudes M and Pickering T (2018) *Case studies on the impact of aquatic exotic species in the Pacific*, Report of the Aquaculture section of the Pacific Community.

Gupta M and Acosta B (2004) 'From drawing board to dining table: The success story of the GIFT Project', *NAGA WorldFish Center Q*, 27:4–14.

Gupta MV, Bartley DM and Acosta BO (2004) 'Use of Genetically Improved and Alien Species for Aquaculture and Conservation of Aquatic Biodiversity in Africa', *The WorldFish Center*, Penang, Malaysia, volume 68.

Harohau D, Blythe J, Sheaves M and Diedrich A (2020) 'Limits of Tilapia Aquaculture for Rural Livelihoods in Solomon Islands', *Sustainability*, 12(4592), **doi:10.3390/su12114592**.

Hinneh MK-Y, Liti MD and Matolla G (2022) 'Characterization of Nile Tilapia (*Oreochromis niloticus*) farming intensities in Liberia', *Aquaculture Journal*, 2:203–215.

Hiruy K and Eversole R (2020) 'The contribution of research for development to the sustainable development goals: Lessons from fisheries research in Southeast Asia and the Pacific island countries', *International Journal of Sustainable Development & World Ecology*, 27:153–166.

IFRC (2023) *Everyone Counts COVID-19; Nobody is safe until everybody is safe*, International Federation of Red Cross, Geneva, Switzerland.

ITC (International Trade Center) (2021) Entrepreneurship ecosystem in the Pacific, Network analysis and mapping of institutions supporting entrepreneurship, ITC.

Jafri S and Ali S (1984) 'Culture of tilapia in Pakistan', *Pakistan Journal of Agricultural Research*, 5:269–276.

Kabir K, Verdegem M, Verreth J, Phillips M and Schrama J (2020) 'Dietary non-starch polysaccharides influenced natural food web and fish production in semi-intensive pond culture of Nile tilapia', *Aquaculture*, 528(735506).

Khalil HS, Momoh T, Al-Kenawy D, Yossa R, Badreldin AM, Roem A, Schrama J and Verdegem M (2021) 'Nitrogen retention, nutrient digestibility and growth efficiency of Nile tilapia (*Oreochromis niloticus*) fed dietary lysine and reared in fertilized ponds', *Aquaculture Nutrition*, 27:2320–2332.

Khanjani MH, Sharifinia M and Hajirezaee S (2022) 'Recent progress towards the application of biofloc technology for tilapia farming', *Aquaculture*, 552(738021).

Limbu SM, Shoko AP, Ulotu EE, Luvanga SA, Munyi FM, John JO and Opiyo MA (2022) 'Black soldier fly (*Hermetia illucens*, L.) larvae meal improves growth performance, feed efficiency and economic returns of Nile tilapia (*Oreochromis niloticus,* L.) fry', *Aquaculture, Fish and Fisheries*, 2:167–178.

Liti D, Cherop L, Munguti J and Chhorn L (2005) 'Growth and economic performance of Nile tilapia (*Oreochromis niloticus* L.) fed on two formulated diets and two locally available feeds in fertilized ponds', *Aquaculture research*, 36:746–752.

Liti D, Mugo R, Munguti J and Waidbacher H (2006) 'Growth and economic performance of Nile tilapia (*Oreochromis niloticus* L.) fed on three brans (maize, wheat and rice) in fertilized ponds', *Aquaculture Nutrition*, 12:239–245.

Little DC and Edwards P (2004) 'Impact of nutrition and season on pond culture performance of mono-sex and mixed-sex Nile tilapia (*Oreochromis niloticus*)', *Aquaculture*, 232:279–292.

Lovell T (1989) 'Tilapia Feeding', *Nutrition and feeding of fish*, New York, Springer.

Macaranas JM, Mather PB, Lal SN, Vereivalu T, Lagibalavu M and Capra MF (1997) 'Genotype and environment: a comparative evaluation of four tilapia stocks in Fiji', *Aquaculture*, 150(1):11–24.

Mather, Peter and Nandlal, Satya (2013) 'Developing sustainable fish farming in the Western Pacific: A viewpoint on potential reasons for why many attempts failed' [editorial], *Pertanika Journal of Tropical Agricultural Science*, 36(4):iii-x.

Ministry of Agriculture and Fisheries, National Directorate of Fisheries and Aquaculture (2013) *Timor-Leste national aquaculture development strategy 2012–2030*, Ministry of Agriculture and Fisheries, Timor-Leste.

Ministry of Development Planning and Aid Coordination (2016) '*National Development Strategy 2016 to 2035: Improving the Social and Economic Livelihoods of all Solomon Islanders'*, **solomons.gov.sb/ministry-of-national-planning-and-development-coordination/**, accessed on 20 January 2025.

Mohan K, Rajan DK, Muralisankar T, Ganesan AR, Sathishkumar P and Revathi N (2022) 'Use of black soldier fly (*Hermetia illucens* L.) larvae meal in aquafeeds for a sustainable aquaculture industry: A review of past and future needs', *Aquaculture*, 553(738095).

Muin H, Taufek NM, Kamarudin MS and Raza SA (2017) 'Growth performance, feed utilization and body composition of Nile tilapia, *Oreochromis niloticus* (Linnaeus, 1758) fed with different levels of black soldier fly, *Hermetia illucens* (Linnaeus, 1758) maggot meal diet', *Iranian Journal of Fisheries Sciences*, 16(2):567–577.

Mwanri AW, Kogi-Makau W and Laswai HS (2011) 'Nutrients and antinutrients composition of raw, cooked and sun-dried sweet potato leaves', *African Journal of Food, Agriculture, Nutrition and Development*, 11:5142–5156.

Narimbi J, Mazumder D and Sammut J (2018) 'Stable isotope analysis to quantify contributions of supplementary feed in Nile Tilapia *Oreochromis niloticus* (GIFT strain) aquaculture', *Aquaculture research*, 49:1866–1874.

Ng WK and Romano N (2013) 'A review of the nutrition and feeding management of farmed tilapia throughout the culture cycle', *Reviews in Aquaculture*, 5:220–254.

Noiney J (2024) 'Factors influencing the growth and production performance of GIFT strain of Nile tilapia (*Oreochromis niloticus*) in satellite hatcheries in Papua New Guinea', Master of Philosophy Thesis, Faculty of Science, The University of New South Wales.

Novogratz A (2023) 'Why $1.4 billion valuation is good news for eFishery and excellent news for the sector as a whole', The Fish Site, **thefishsite.com/articles/why-1.4-billion-valuation-is-good-news-for-efishery-and-excellent-news-for-the-sector-as-a-whole**, accessed on 10 July 2023.

NSW Government (n.d.) Tilapia (web page), NSW Government Department of Primary Industries and Regional Development, **nsw.gov.au/fishing/aquatic-biosecurity/pests-diseases/freshwater-pests/finfish-species/tilapia#:~:text=Tilapia%20were%20historically%20imported%20to,possess%2C%20sell%20or%20move%20Tilapia**, accessed 28 October 2024.

Ogello EO, Musa SM, Aura CM, Abwao JO and Munguti JM (2014) *An appraisal of the feasibility of tilapia production in ponds using biofloc technology: A review.*

Omasaki S, Janssen K, Besson M and Komen H (2017) 'Economic values of growth rate, feed intake, feed conversion ratio, mortality and uniformity for Nile tilapia', *Aquaculture*, 481:124–132.

O'Meara L, Cohen PJ, I'ilu Kafa R, Wate JT, Albert J, Bogard J, Bonis-Profumo G, Burkhart S, Delisle A, Diffey S, Eria T, Farmery A, Fukofuka K, Mangubhai S, Mitchell MEV, Na'ati E, Nyemah JN, Pickering T, Sutcliffe S, Swanepoel L, Thilsted SH and Lam FV (2023) 'Pacific food systems – The role of fish and other aquatic foods for nutrition and health', *Apia*, FAO, **doi.org/10.4060/cc5796en**.

Pant J (2023) 'How the Rise of Timor-Leste's Aquaculture Sector is a Blueprint for Other Small Island Nations', Inter Press Service, News Agency, *News and Views from the Global South*, published on 3 May 2023, **https://www.ipsnews.net/2023/05/rise-timor-lestes-aquaculture-sector-blueprint-small-island-nations/#google_vignette**

Pant J, Bhujel RC, Du Karmu AD, Soares de Jesus L, Gomes S, Pereira A, Pereira M and Teoh SJ (2024) 'Sustainable production and dissemination of genetically improved farmed tilapia seed in smallholder farming systems: A case study from Timor-Leste', *Agricultural Systems*, 219(104031), Elsevier, **sciencedirect.com/science/article/pii/S0308521X24001811**.

Pant J, Gomes S, Teoh SJ, Pereira A, De Jesus LS, Karmu ADFd, Pereira M, Shrestha MK and Bhujel RC (2023), *Better management practices (BMP) for grow-out farming of Genetically Improved Farmed Tilapia (GIFT) in Timor-Leste,* WorldFish, Manual 2023-52, Penang, Malaysia, **digitalarchive.worldfishcenter.org/bitstream/handle/20.500.12348/5648/8ba3f3e3d1151d5ef84068b5b7df1ffb.pdf?sequence=2&isAllowed=y**.

Pant J, Guttres A, Pereira M, Gomes S, DuKarmu ADF, DeJesus LS, Pereira A, Timsina J and Bhujel RC (29 May to 1 June 2023) 'Sustainable scaling-up of small-scale aquaculture in Timor-Leste: a model of success but still there are challenges', Book of Abstracts, *World Aquaculture Society conference*, Darwin, Australia.

Pant J, Perera M, Jusadi D, Gomes S, Pandit NP, Bhujel RC and Timsina J (2023) 'Potential for producing tilapia (*Oreochromis niloticus*) feed using locally sources ingredients in resource-poor farming systems: A case study from Timor-Leste', *The Aquafeed Journal*, 1, **issuu.com/international_aquafeed/docs/iaf2307_w1**.

Pant J, Salu R, Bhujel RC, Teoh SJ, Gomes S and Timsina J (2024) *Report of the Third Timor-Leste National Aquaculture Forum (NAF3)*, WorldFish, Program Report 2024-52, Penang, Malaysia, **hdl.handle.net/10568/163392**.

Pant J, Teoh SJ, Gomes S, Pereira A, Pereira M, Soares de Jesus L, Du Karmu AD and Bhujel RC (2024) 'Sustainable intensification of genetically improved farmed Tilapia (GIFT) in Timor-Leste's farming systems: Challenges and opportunities', *Agricultural Systems*, 216 (103874), Elsevier, **sciencedirect.com/science/article/pii/S0308521X24000246**.

Pant J, Teoh S, Gomes S, Chadag V, De Jesus L and Pereira M (2019) 'Better management practices for genetically improved farmed tilapia (GIFT) in Timor-Leste', *Sustainable aquaculture*, 2829, **hdl.handle.net/20.500.12348/3742**.

Pant J, Teoh S, Gomes S, Pereira M and Kam S (2020) *Partnership for aquaculture development in Timor-Leste: Looking back, looking forward*, Program Brief: 2020–11, WorldFish, Malaysia.

Parata L, Mazumder D, Sammut J and Egan S (2020) 'Diet type influences the gut microbiome and nutrient assimilation of Genetically Improved Farmed Tilapia (*Oreochromis niloticus*)', *Public Library of Science (PLOS)*, 1(15), e0237775.

Parata L, Noiney J, Majzoub ME, Mazumder D, Egan S and Sammut J (2023) 'The role of farming practice in nutrient assimilation in small-scale tilapia farming', *Aquaculture*, 563(739005).

Pirozzi I, Pickering T and Lal M (2011) *Pacific islands aquaculture feed ingredients inventory* (MS1007) in Hair C and Southgate P (2013) *Developing aquaculture-based livelihoods in the Pacific islands region and tropical Australia,* FIS/2006/138, Final Report, Australian Centre for International Agricultural Research, Canberra, Australia.

Pickering T (2010) 'Tilapia fish farming in the Pacific: A responsible way forward', *SPC Fisheries Newsletter*, 130:24–26.

Pickering (2015) 'South Santo tilapia farmers gear up to increase production' *SPC Fisheries Newsletter*, 147:2–4.

Pickering (2016) 'Samoa villagers celebrate first fish harvest from tilapia floating-cage aquaculture system' *SPC Fisheries Newsletter,* 150:25.

Ponia B (2003) 'Aquaculture update for Vanuatu' in volume 105, Secretariat of the Pacific Community, Noumea, New Caledonia.

Ponia B (2010) 'A review of aquaculture in the Pacific Islands 1998–2007: tracking a decade of progress through official and provisional statistics', Secretariat of the Pacific Community (SPC), Noumea, New Caledonia.

Prabu E, Rajagopalsamy CBT, Ahilan B and Jegan Michael Andro JeevaganI Renuhadevi M (2019) 'Tilapia – An Excellent Candidate Species for World Aquaculture: A Review', *Annual Research & Review in Biology, 31(3):1–14.*

Pullin RSV (ed) (1988) 'Tilapia genetic resources for aquaculture', *ICLARM Conference* proceedings 16, Manila, Philippines.

Pullin RSV and JB Capili (1988) 'Genetic improvement of tilapias: problems and prospects' (259–266) in Pullin RSV, Bhukaswan T, Tonguthai K and Maclean JL (eds) *The Second International Symposium on Tilapia in Aquaculture, ICLARM Conference proceedings 15, Department of Fisheries, Bangkok, Thailand, and ICLARM, Manila, Philippines.*

Queensland Government (2024) Tilapia (Oreochromis mossambicus and Tilapia mariae) – fact sheet, Queensland Government, **daf.qld.gov.au/__data/assets/pdf_file/0009/1238076/tilapia.pdf**, accessed on 28 October 2024.

Romana-Eguia, MRR, Larona MA and Catacutan MR (2013) 'On-farm feed management practices for Nile tilapia (*Oreochromis niloticus*) in the Philippines', *On-farm feeding and feed management in aquaculture*, FAO Fisheries and Aquaculture, Rome, Technical Paper 583, 131–158.

Roscher MB, Allison EH, Mills DJ, Eriksson H, Hellebrandt D and Andrew N L (2022) 'Sustainable development outcomes of livelihood diversification in small-scale fisheries', *Fish and Fisheries*, 23:910–925, **dx.doi.org/10.1111/faf.12662**.

Salger SA, Reza J, Deck CA, Wahab MA, Baltzegar DA, Murr AT and Borski RJ (2020) 'Enhanced biodiversity of gut flora and feed efficiency in pond cultured tilapia under reduced frequency feeding strategies', *PLOS*, 1(15), e0236100.

Sammut J, Vira H, Tong S, Nicholl M, Noiney J, Mazumder D, Wani J, Hiruy K and Lau SM (2024) 'Towards Food, Nutrition and Income Security in Papua New Guinea Through Inland Fish Farming' (445–471) in *Water Security in a New World*, Springer International Publishing, **doi:10.1007/978-3-031-25463-5_20**.

Sammut J, Wani J, Noiney J, Vira H, Mazumder D, Aranka M, Alois A, Egan S, Hiruy K, Tong S, Nicholl M, Kerowa B and Kagl P (2021) *Improving technologies for inland aquaculture in PNG*, Australian Centre for International Agricultural Research, Canberra.

Santos VBd, Mareco EA and Dal Pai Silva M (2013) 'Growth curves of Nile tilapia (*Oreochromis niloticus*) strains cultivated at different temperatures', Acta Scientiarum, *Animal Sciences*, 35:235–242.

Saravanan S, Geurden I, Figueiredo-Silva AC, Kaushik SJ, Haidar MN, Verreth JA and Schrama JW (2012) 'Control of voluntary feed intake in fish: a role for dietary oxygen demand in Nile tilapia (*Oreochromis niloticus*) fed diets with different macronutrient profiles', *British Journal of Nutrition*, 108:1519–1529.

SDG Gateway (2023) *Is Asia-Pacific on track to achieve the SDGs?,* SDG Progress Report 2023, **data.unescap.org/home**.

Shearer (2000) 'Experimental design, statistical analysis and modelling of dietary nutrient requirement studies for fish: a critical review', *Aquaculture nutrition*, 6:91–102.

Shelomi M (2020) 'Potential of Black Soldier Fly Production for Pacific Small Island Developing States', *Animals*, 10(1038), **doi.org/10.3390/ani10061038**.

Sievert K, Lawrence M, Naika A and Baker P (2019) 'Processed foods and nutrition transition in the Pacific: regional trends, patterns and food system drivers', *Nutrients*, 11(1328).

Sine M, Roberts A, Ayalew W, Vira H and Booth MA (2017) 'Growth performance of juvenile genetically improved farmed tilapia (GIFT) fed a feed concentrate blended with cassava or sweet potato' in Glatz P (ed) *Local feed resources for pig, poultry and fish production in Papua New Guinea*, Australian Centre for International Agricultural Research, Canberra.

Smith IR and Pullin RSV (1984) 'Tilapia production booms in the Philippines', *ICLARM Newsletter* 7:7–9.

Smith PT (ed) (2007) *Aquaculture in Papua New Guinea: status of freshwater fish farming, ACIAR Monograph No. 125, p 124.*

SPC (2022) 'Strengthening the voice of Pacific fishers: FAO, SPC and INFOFISH launch the International Year of Artisanal Fisheries and Aquaculture (IYAFA 2022) in the Pacific, *SPC News*.

SPC (2023) *Women in Fisheries Information Bulletin* 37:1–69.

Susumu G (2014) 'Snapshots of food and nutrition security in the Pacific Region' prepared for the *IFPRI 2020 Vision Initiative Policy Consultation Conference on Building Resilience to Food and Nutrition Security, Addis Ababa, 15–17 May 2014, Secretariat of the Pacific Community, Noumea, New Caledonia,* **capacity4dev.europa.eu/library/snapshots-food-and-nutrition-security-pacific-region-gibson-susumu-spc_en**, accessed on 13 January 2025.

Tacon A (1995) 'Application of nutrient requirement data under practical conditions: special problems of intensive and semi-intensive fish farming systems', *Journal of Applied Ichthyology*, 11:205–214.

Tavares FA, Rodrigues JBR, Fracalossi DM, Esquivel J and Roubach R (2008) 'Dried duckweed and commercial feed promote adequate growth performance of tilapia fingerlings', *Biotemas*, 21(3):91–97.

Tavares FA, Lapolli FR, Roubach R, Jungles MK, Fracalossi DM and Moraes Ad (2010) 'Use of domestic effluent through duckweeds and red tilapia farming in integrated system', *Pan-American Journal of Aquatic Sciences*, 5:1–10.

Teichert-Coddington D and Green BW (1993) 'Tilapia yield improvement through maintenance of minimal oxygen concentrations in experimental grow-out ponds in Honduras', *Aquaculture*, 118:63–71.

Tippayadara N, Dawood MA, Krutmuang P, Hoseinifar SH, Doan HV and Paolucci M (2021) 'Replacement of fish meal by Black soldier fly (*Hermetia illucens*) larvae meal: Effects on growth, haematology, and skin mucus immunity of Nile Tilapia, *Oreochromis niloticus*', *Animals*, 11(193).

Tran-Duy A, van Dam AA and Schrama JW (2012) 'Feed intake, growth and metabolism of Nile tilapia (*Oreochromis niloticus*) in relation to dissolved oxygen concentration', *Aquaculture Research*, 43:730–744.

Tran-Ngoc KT, Dinh NT, Nguyen TH, Roem AJ, Schrama JW and Verreth JAJ (2016) 'Interaction between dissolved oxygen concentration and diet composition on growth, digestibility and intestinal health of Nile tilapia (*Oreochromis niloticus*)', *Aquaculture*, 462:101–108.

UNCTAD (United Nations Conference on Trade and Development) (2022) *Digital Economy Report, Pacific Edition 2022, Towards Value Creation and Inclusiveness*, United Nations Publications issued by the United Nations Conference on Trade and Development.

United Nations (n.d.) Sustainable Development Goals website (statistics), UN, **unstats.un.org/sdgs/**, accessed 28 October 2024.

Vereivalu T (1989) 'Aquaculture activities in Fiji' *Actes de colloques Ifremer*, Tahiti, French Polynesia, 20 February to 4 March 1989, 9(3):31–36, **archimer.ifremer.fr/doc/00000/1498/**.

Wang Y-S and Shelomi M (2017) 'Review of Black Soldier Fly (*Hermetia illucens*) as Animal Feed and Human Food', *Foods*, 6(10): 91, **doi.org/10.3390/foods6100091**.

Wangkahart E, Bruneel B, Wisetsri T, Nontasan S, Martin SAM and Chantiratikul A (2022) 'Interactive effects of dietary lipid and nutritional emulsifier supplementation on growth, chemical composition, immune response and lipid metabolism of juvenile Nile tilapia (*Oreochromis niloticus*)', *Aquaculture*, 546.

Waqairatu-Waqainabete S, Lal M, Cavakiqali L, Simos T and Southgate P (2022) *Live Tilapia Market Demonstration Pilot, Lautoka, Fiji,* Final Report, Pacific Research for Development Initiative (PARDI 2) (AGB/2014/057), Australian Centre for International Agricultural Research (ACIAR).

Webster CD, Rawles SD, Koch JF, Thompson KR, Kobayashi Y, Gannam AL and Hyde NM (2016) ‘Bio-Ag reutilization of distiller’s dried grains with solubles (DDGS) as a substrate for black soldier fly larvae, *Hermetia illucens*, along with poultry by-product meal and soybean meal, as total replacement of fish meal in diets for Nile tilapia, *Oreochromis niloticus*’, Aquaculture Nutrition, 22:976–988.

Yi Y and Lin CK (2001) ‘Effects of biomass of caged Nile tilapia (*Oreochromis niloticus*) and aeration on the growth and yields in an integrated cage-cum-pond system’, *Aquaculture*, 195:253–267.

Yildirim-Aksoy M, Eljack R, Schrimsher C and Beck BH (2020) ‘Use of dietary frass from black soldier fly larvae, *Hermetia illucens*, in hybrid tilapia (Nile x Mozambique, *Oreocromis niloticus* x *O. mozambique*) diets improves growth and resistance to bacterial diseases’, *Aquaculture Reports*, 17(100373).

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