sustainability

MDPI

Article

Assessment of Tilapia–Freshwater Prawn Co-Culture Schemes in Tanks and Lake-Based Cages for Increased Farm Production

Maria Rowena Robles Romana-Eguia [1,*], Mildred Patito Rutaquio [1], Reylan Caroscos Gutierrez [1] and Nerissa Diaz Salayo [2]

[1] Southeast Asian Fisheries Development Center, Aquaculture Department, Binangonan Freshwater Station, Binangonan 1940, Rizal, Philippines; mrutaquio@seafdec.org.ph (M.P.R.); rgutierrez@seafdec.org.ph (R.C.G.)
[2] Southeast Asian Fisheries Development Center, Aquaculture Department, Tigbauan Main Station, Tigbauan 5021, Iloilo, Philippines; ndsalayo@seafdec.org.ph
* Correspondence: mreguia@seafdec.org.ph

Abstract: The technical viability of tilapia (I-ExCEL strain Nile or red) and giant freshwater prawn (GFP) co-culture in cages-within-tanks was evaluated while appropriate feeding protocols for tilapia-GFP co-culture in cages in a eutrophic lake were determined. Specifically, production parameters in all test species grown for five months in tank co-culture (where only tilapias were fed) were compared, while the best feeding protocol from among the following treatments: (a) T_{fed}—fed tilapias; (b) GFP_{fed}—fed prawns and (c) T-GFP_{fed}—both species fed, were defined. I-ExCEL Nile tilapias grew faster in tank co-culture whether reared singly or otherwise. However, red tilapia-GFP tank co-culture gave the best results considering key production traits in all test species (red tilapia—2.52%/day specific growth rate or SGR, 83.3% survival; GFP—1.17%/day SGR, 72.85% survival). Lake-based co-culture was technically feasible at stocking densities of 12.5/m^2 for tilapia and 2.4 to 4/m^2 for prawns even when only tilapias were fed; prawns grew to desired marketable sizes by thriving mainly on detritus and natural food organisms in the lake. However, further refinements can still be made to optimise the co-culture schemes to make them more sustainable and provide artisanal fish farmers options in increasing farm yields through multi-species aquaculture.

Keywords: Nile and red tilapia; giant freshwater prawn; lake cages; co-culture

Citation: Romana-Eguia, M.R.R.; Rutaquio, M.P.; Gutierrez, R.C.; Salayo, N.D. Assessment of Tilapia–Freshwater Prawn Co-Culture Schemes in Tanks and Lake-Based Cages for Increased Farm Production. *Sustainability* **2021**, *13*, 13574. https://doi.org/10.3390/su132413574

Academic Editor: Mario D'Amico

Received: 30 October 2021
Accepted: 6 December 2021
Published: 8 December 2021

1. Introduction

The COVID-19 pandemic has adversely affected the global economy, in general various food production industry sectors, in particular. This health crisis has clearly affected the entire aquaculture industry's value chain, especially in major fish producing countries in Southeast Asia. Lockdowns caused interruptions in aquaculture operations due to restrictions in transporting inputs such as seedstock, feeds, etc., as well as constraints in fish processing and trade. These quarantine restrictions have adversely impacted the vulnerable small scale fish farmers who comprise a majority of the fish production industry sector in developing countries [1]. The current major concern for developing and/or low-income countries engaged in fish farming is how to continuously operate fish farms, supply local markets and, where applicable, export aquatic commodities as was usual during the pre-pandemic period. Fish exports have become challenging given the constraints in international travel; however, one coping mechanism for farmers would be to instead concentrate on producing more food fish for the domestic retail and wholesale market [2]. Thus, this has become advantageous for the marginalized fish farmer who should be encouraged to increase their fish yield by adopting field-verified, optimal fish farming technologies. Traditional, small-scale fish farmers, especially in developing states such as the Philippines, often engage in monoculture or single-species fish farming since this has consistently assured them of steady fish yields. However, opportunities to earn more income from fish farming can be realized if product diversification is done through multi-species aquaculture, for example via co-culture, polyculture and/or integrated fish farming.

Tilapias are a globally-traded, low-input species produced mostly in Asia through small- to medium-scale aquaculture. The tilapias are traditionally farmed singly although some countries, such as Thailand, Malaysia, China, etc., practice pond-based tilapia co-culture, polyculture and integrated farming with either marine shrimps and/or prawns [3]. On the other hand, while prawns are also produced in monoculture and traded domestically in Asia, a considerable proportion of the global production of this commodity comes from polyculture and integrated farming [4]. Prawn monoculture has been practiced using extensive, mixed and semi-intensive culture systems in ponds and reservoirs especially in South Asia, from small farm holding areas to large facilities [5]. Low-input fish species such as tilapias (Nile, red and other *Oreochromis* species) or carps (catla *Catla catla*, rohu *Labeo rohita*, silver carp *Hypopthalmicthys molitrix*) have been jointly farmed with freshwater prawns mainly in earthen ponds and, for some, in integrated farming (rice-prawn, etc.) systems in Thailand, China, Bangladesh, India, Vietnam, etc. [4,6].

Several methods have been tried, including the use of a biofloc technology system in tilapia–prawn polyculture as an effective eco-friendly aquaculture model in producing multiple species [7] apart from the pond-based polyculture of other tilapia species such as red tilapia hybrids with giant freshwater prawns, using batch or continuous culture systems [8]. Although the requirements for tilapia–prawn co-culture in ponds and reservoirs have been known, methods for rearing both species simultaneously in small-scale backyard tank and lake-based, cage rearing systems have not been tried. The importance of these efforts comes with the need to support subsistence aquaculture as well as generate additional income for fish farmers, especially those in lakeshore communities.

In the Philippines, tilapias are third among the top five priority species for aquaculture production, the others being seaweeds, milkfish, marine shrimps and shellfish (mussels and oysters). In terms of finfish production, tilapias rank second to milkfish in Philippine aquaculture [9] given the ease by which this species is propagated and reared to marketable sizes, since breeding and farming technologies are well established [10–12]. In 2018, an estimated 279,385.87 metric tons of tilapia were produced in aquaculture, coming mainly from freshwater and brackish-water ponds, fish cages and fish pens (with some 1.69 metric tons from marine fish pens) [9]. Several genetically improved tilapia strains, which have been selected for desirable traits (e.g., fast growth, high survival), are readily available to fish farmers since most of the selected stocks have been developed in Southeast Asia, largely in the Philippines [13].

Meanwhile, the giant freshwater prawn *Macrobrachium rosenbergii* has been domesticated, bred in captivity and, although limited in scale, grown in monoculture in the Philippines, particularly in ponds and, recently, in experimental lake-based cages [14–16]. Freshwater prawn production in the Philippines in 2018 was low and negligible at 1.25 metric tons [9]. This limited commercial production is in contrast to those of other prawn producing countries such as Thailand, Taiwan, Bangladesh, Vietnam and India [3] even if *Macrobrachium* spp. and other related Caridean species are native to the Philippines [17]. Although local research started in 1980 from prawn breeding and larval rearing to small-scale prawn culture, rice-prawn and tilapia–prawn by BFAR and SEAFDEC/AQD and, more recently, lake-based cage farming by SEAFDEC/AQD, efforts to promote prawn farming to boost local production have not been as aggressive as compared to marine shrimp aquaculture.

In 2015, the World Fish Center supported a nationwide participatory learning and fish farmer engagement project to revive interest in prawn production in the Philippines. This study involved 17 small scale farmer cooperators from six regions in the Philippines who tried to produce prawns using various pond culture systems from monoculture, prawn–rice polyculture and prawn–tilapia culture [18]. Production outputs were compared, and constraints were identified that could help formulate policy recommendations for the sustainable development of freshwater prawn culture in the Philippines. One of the limitations identified by this study was seedstock source. Several of the prawn grow-out farms, where trials for this 2015 study was conducted, obtained prawn postlarvae and/or juveniles from the Binangonan Freshwater Station (BFS) of SEAFDEC/AQD where our current study has been conducted. The research station is strategically located along the shores of Laguna de Bay or Laguna Lake and has for years been operating a small scale giant freshwater prawn hatchery that provides seedstock both for research and for use by prawn small scale grow-out operators. Ironically, in spite the availability of prawn cage farming technologies developed by Cuvin-Aralar et al. [14,16] and the proximity of the SEAFDEC/AQD prawn hatchery to Laguna Lake where Nile tilapias are commercially grown in net cages, prawn culture in the lake has not been widely adopted. With this in mind, and since in earlier studies lake-based prawn production has been proven to be technically feasible [16], this study was conducted with the aim of promoting prawn farming in cages to local farmers in the lakeshore communities. Moreover, the possibility of developing viable small-scale tilapia–prawn co-culture techniques by growing either a genetically improved Nile tilapia strain such as the I-ExCEL or a red tilapia hybrid in cages within backyard concrete tanks are explored to promote subsistence aquaculture.

Most of the tilapia species farmed in the Philippines are the Nile tilapias, some of which are strains selected for fast growth, while some use farmer's strains. Red tilapias, on the other hand, are not as commonly farmed as the Nile tilapias. These hybrids cater to a special niche market hence any production, although limited, still contributes to the total national tilapia production. It is known though that the red tilapias which are marketed live in supermarkets and served in specialty restaurants are sold at USD 2.40 per kg in the Philippines, or twice the market price of the Nile tilapias. Red tilapia is a good alternative to Nile tilapia and in other countries (e.g., Malaysia, Columbia, Jamaica, India, Thailand and Bangladesh) where these are commercially produced, red tilapias have been successfully traded because of its attractive colour, fast growth rate (especially in brackishwater [19]) and good market demand [20]. On the other hand, depending on the size, giant freshwater prawns are sold at USD 5.00 to USD 7.00 per kg. Hence considering the value of the traded GFP and red tilapias, if these would be cultured in the same facility or enclosure as the traditionally cultured Nile tilapias, farmers would earn more. Apart from increased income, what makes a fish–prawn polyculture system ideal regardless of the enclosure used, is the fact that prawns when reared with other species have synergistic beneficial effects on: (a) the quality of the rearing water (more stable dissolved oxygen levels especially in ponds); (b) reduction of predators; (c) coprophagy (or the consumption of fish faeces by the prawns) which aids feeding efficiency and (d) greater total productivity (all species) [4].

Recent studies on the co-culture of a genetically improved Nile tilapia strain (GIFT) and red tilapia hybrids with prawns in ponds have been conducted [21]. However, fish–prawn co-culture involving two tilapia species such as Nile and/or red hybrids as primary commodities has not been tried in small-scale tank and lake-based cage farming facilities. In the present study, we used the I-ExCEL Nile tilapia strain which was developed from a GIFT-derived strain known as the GET-ExCEL [13,22]. Based on BFAR records, the Improved GET-ExCEL or I-ExCEL has an average fillet percentage of 36%, grew by an additional 53–58 g over the 8th generation GIFT and is observed to withstand temperature fluctuations [20,23]. Our study aimed to assess the merits of simultaneously rearing two to three commercially valuable species (I-ExCEL Nile and/or red tilapia with giant freshwater prawn) in tank and lake co-culture systems during the wet and dry seasons. Should this be noted as technically viable, such methods can be considered for artisanal aquaculture especially in inland and lakeshore communities. Hence, preliminary technical evaluations to determine the feasibility of (a) rearing a genetically improved Nile tilapia strain (I-ExCEL) or red tilapia singly or in co-culture with giant freshwater prawns (GFP) in a cage-in-tank system and (b) adopting different feeding schemes for Nile and red tilapia–prawn co-culture in lake-based cages were conducted.

2. Materials and Methods

2.1. Stocks Used

A genetically improved Nile tilapia strain ("I-ExCEL" which is a "GET ExCEL" derived strain) was procured from the Philippine Department of Agriculture's Bureau of Fisheries and Aquatic Resources (DA-BFAR) facility in Muñoz, Nueva Ecija, Philippines. The I-ExCEL Nile tilapia is the most recent genetically improved Nile tilapia (based on a composite tilapia strain, "GET-ExCEL", which is partially derived from the Genetically Improved Farmed Tilapia, or "GIFT", strain [13,22]), being disseminated by the DA-BFAR facility in Nueva Ecija. The red tilapia fingerlings were obtained from a local commercial farm in Laguna, Philippines while the giant freshwater prawn *Macrobrachium rosenbergii* juveniles were also obtained from DA-BFAR. All the tilapia and prawns used in the study are mixed sex.

2.2. Experimental Facility

The trials were conducted at SEAFDEC/AQD's Binangonan Freshwater Station in Binangonan, Rizal, Philippines. This island station is located along the shore of Laguna de Bay, one of the largest lakes in the Philippines with an average depth of 2.5 m^2 and an area of 900 km^2. The research station has facilities for both land and lake-based experiments and as well as for small scale production of tilapia, prawn, bighead carp, Asian catfish and silver perch seedstock.

For the tank-based trials, $1 \times 1 \times 1$ m^3 B-net (5 mm mesh) cages which held the tilapias were installed in $2 \times 2 \times 1$ m^3 outdoor concrete tanks where the prawns were directly stocked. For the lake-based trials, $2 \times 2 \times 1$ m^3 B-net cages for the tilapias were set up within $5 \times 5 \times 1.5$ m^3 fine-meshed hapa net cages containing the prawn juveniles.

2.3. Tank-Based Tilapia–Prawn Co-Culture Experiment

A 2×2 factorial, completely randomized design experiment with three replicates was conducted using the following treatments—(a) NileMONO, or I-ExCEL Nile tilapia monoculture; (b) NileCO, or I-ExCEL Nile tilapia–prawn co-culture; (c) RedMONO, or Red tilapia monoculture and (d) RedCO, or Red tilapia–prawn co-culture. Two rearing runs were conducted, one each during the wet (June to October 2020) and dry (February to July 2021) seasons. I-ExCEL Nile and/or red tilapia fingerlings (mean initial weight = 5.8 g) were stocked in the B-net cages at 10 fish/m^2 (based on cage bottom dimensions), while the prawns (mean initial weight = 3.9 g) were stocked directly in the outdoor concrete tanks at 7.5 prawns/m^2. The tilapias are caged to minimize antagonistic behavior towards the prawns [24]. Meanwhile, since studies have shown that mean size at harvest, daily growth rate and size class distribution in prawns when reared in aquaculture are significantly influenced by stocking density, among other factors, low prawn stocking densities were used for our trials [16]. Two units of 100 cm × 80 cm nets were then hung vertically in the water in each tank to serve as hides or shelters for the prawns. Only tilapias were fed twice daily with commercially available sinking feeds containing 30% crude protein, 6% crude fat, 6% crude fiber, 12% ash and 12% moisture. This followed the recommended crude protein content for growing tilapia, which is 28–30% [25]. The feeding rate adopted started at 10% of the fish biomass and was adjusted (reduced to 7%, 5%, then 3%) once every two weeks until a feeding rate of 2% of the fish biomass was given at the end of the five-month rearing period.

2.4. Lake-Based Tilapia–Prawn Co-Culture Feeding Management Experiment

Tilapias are usually farmed extensively in cages in Laguna de Bay following stocking densities ranging from 15–25/m^3 [12] and fed supplemental diets to add to the natural food found in the lake. For this present study, to ensure good growth and survival, a lower tilapia stocking density in the lake cages was also used. Twenty-five pieces each of the I-ExCEL Nile tilapias and red tilapias (mean initial weight = 3.7 g), or a total tilapia stocking density of 12.5/m^2 or 12.5/m^3 (given a 1 m cage depth), were stocked in $2 \times 2 \times 1$ m^3 B-net cages set inside 5 × 5 × 1.5 m^3 hapa net cages which held the prawn juveniles (mean initial weight—3.2 g). The cage-within-cage setup was adopted to prevent antagonistic behavior, if any, of tilapias towards the prawns which are co-inhabiting the rearing enclosure [22]. Moreover, it has been observed in some studies on tilapia–prawn polyculture that tilapias, when kept in cages, do not adversely affect the prawns in terms of their growth and the resulting population structure (e.g., % of sex) [26]. Likewise, apart from the fact that farmers prefer having caged tilapias when doing tilapia–prawn polyculture especially in ponds, for ease in harvesting, tilapias being confined in cages, have often resulted to increased or high total tilapia production without affecting prawn production [27]. As for the prawns, fine-meshed hapa net cages were used in this experiment since an earlier study [14] has shown that prawns reared in hapa net cages in the same lake (Laguna de Bay, Philippines) gave better overall performance. Cuvin-Aralar et al. [14] noted that the hapa net cage has effectively reduced the entry of predator and competitor species and allowed more natural food to be trapped in the cages, thus providing an additional food source for growing prawns.

The lake cage-feeding experiment followed a completely randomized design with three replicates comparing three feeding schemes, namely—(a) T_{fed}—only tilapias were fed; (b) GFP_{fed}—only prawns fed commercial sinking shrimp feeds and (c) T-GFP_{fed}—both species were fed. The tilapias, when fed, were administered a commercially available tilapia floating diet containing 29% crude protein, 6% crude fat, 6% crude fiber, 12% ash and 12% moisture. On the other hand, the prawns when fed, were given a commercially available sinking shrimp feed containing 40% crude protein, 6% crude fat, 4% crude fiber, 17% ash and 12% moisture. Although the recommended crude protein content for semi-intensive freshwater prawns culture is 30–35% [4], a marine shrimp diet was used in the study in the absence of a commercially available diet for freshwater prawns in the Philippines. Two runs, one during June 2020–October 2020 (wet season) and another during March 2021–July 2021 (dry season), were conducted. In the wet season run, the prawns were stocked at a low density of 2.4 prawns/m^2 (or n = 60 prawns), based on the cage-bottom area. A slightly higher prawn stocking density of 4 prawns/m^2 (or n = 100 prawns) was used in the dry season run. In the lake-based trials, feeding rations for the tilapias were similar to the tank-based co-culture runs, and prawn feed rations also followed the same sliding scheme ration [4]. Four net shelters made from polyethylene net (mesh size:13 knots; 2.54 cm) measuring 100 cm × 80 cm were hung vertically within the hapa net enclosures to serve as hides for the prawns [16].

2.5. Sampling and Monitoring

Length and weight measurements were taken monthly from individual samples during which head counts of the different species were noted for survival rate computation. The amount of feeds (based on % biomass) were adjusted based on both bulk and individual weight measurements on a mid-month and monthly basis, respectively. Using a portable Horiba Water Quality Checker Model U-10 (Horiba Ltd., Kyoto, Japan), basic physico-chemical parameters (temperature, dissolved oxygen, pH, ammonia) were taken once a week from the rearing set-ups, at 0800H and 1600H, for water quality monitoring. Water transparency was noted using a Secchi disc [16]. Water samples were also taken from lake-based cages to monitor primary productivity at the time of rearing. The major planktons were identified under the microscope and estimated by counting cells in the water sample loaded onto a haemacytometer. The water samples were triplicate aliquots taken from previously filtered lake water samples.

2.6. Data Analysis

Growth in terms of average weight gain (AWG = final average weight − initial average weight) and specific growth rate [SGR = ($ln(W_{final}) - ln\ (W_{initial})$)/days of culture × 100] were computed. W_{final} and $W_{initial}$ means final weight of the test species and initial weight, respectively while *ln* refers to natural logarithm. Feed conversion ratios (FCR) computed as the actual weight of feed presented divided by the actual weight of fish or prawns were produced [4], and % survival was also estimated. All these parameters were used in the statistical analysis to determine differences in the various experimental treatments. The effects of independent variables such as tilapia species (I ExCEL Nile, red) and scheme (monoculture, co-culture) on the growth parameters (average weight gain, AWG; specific growth rate, SGR) and feed conversion ratio (FCR) of tilapias in the tank study were analysed by a two-way analysis of variance (ANOVA) via SYSTAT [28]. As for the lake-based feeding study, the effect of feeding treatment on the growth and survival of the tilapias and prawns were analysed via one-way ANOVA. Tukey's HSD was conducted following significant ANOVA results to determine differences between treatment means. All of the analyses were completed separately for each season or run.

2.7. Economic Analysis of Feeding Efficiency

Although this paper focuses primarily on the technical viability of the various co-culture schemes, a feeding efficiency economic analysis has been included. The feeding efficiency economic analysis explains how growth (in terms of weight increment) in the different species and feed input costs can be analysed to enable an understanding of optimal practical feeding management protocols in the different co-culture schemes used.

The economic efficiency of feeding using commercially available tilapia pellets as applied to all treatments were evaluated in terms of the marginal change in output-per-unit increase in input applied. In particular, the periodic change in the total biomass or weight of the fed and the un-fed species in the experiments were evaluated against the periodic total expenditure on feeds. A period covers the 14-day interval between sampling or data collection period. Daily weight gain refers to the average daily increase in weight of the fed species. A unit increase in input or feed applied refers to the daily feed ration multiplied by the unit market cost of feed. The daily ration is determined during each 14-day interval sampling period based on the weight of the fed species during each sampling. Weight increment-per-unit increase in feed expenditure is determined for the following setups: (1) tank setup, wet (run 1) and dry (run 2) seasons and (2) lake setup, wet (run 1) and dry (run 2) seasons.

3. Results

3.1. Tilapia Monoculture vs. Tilapia–Prawn Co-Culture in Tanks

A summary of the growth, survival and feed conversion ratio for the Nile and red tilapia farmed in net cages within tanks for the two runs is presented in Table 1. The results of the same production parameters for the unfed prawns stocked directly in the tanks during the five-month rearing period were also included.

Regardless of the culture scheme, growth of the I-ExCEL Nile tilapias (AWG: 181.6–239.4 g; SGR: 2.15–2.89%/day) in the net cages set in tanks were generally better than that of the red tilapias (AWG: 110–143.7 g; SGR: 2.02–2.52%/day) in both runs (Table 1, Figure S1 in Supplementary material A). Although not significantly different, survival percentages were slightly better in the red tilapias (76.7–95%) in both mono and co-culture systems compared to the I-ExCEL Nile tilapias (75–90%) in both runs (Figure S2 in Supplementary material A). A two-way ANOVA was completed to look into the effect of the type of treatment (culture scheme) and species on growth (AWG). Results showed no significant treatment effects (system and species) on growth (AWG, SGR) during the wet season $p = 0.17$, while both AWG and SGR were significantly different during the dry season as influenced by treatment ($p = 0.03$).

Feed conversion ratios for the I-ExCEL Nile tilapia reared in monoculture and co-culture were slightly lower, at 1.81 to 1.95, than the estimated ratios for the red tilapias at 1.99 to 2.13 (Table 1).

For the prawns grown in co-culture with either I-ExCEL Nile or red tilapias, specific growth rate ranged from 1.15 to 1.30%/day. Prawn growth (AWG:13.8 and 20.2 g; SGR: 1.17 and 1.30%/day) and survival (32 and 72.3%) were noticeably at par or even higher in those co-cultured with red tilapias in both runs (Figures S1 and S2 in Supplementary material A). Prawn survival in run 2 or during the dry season were significantly higher (51–72.3%) than those in the wet season (10–32%) (Table 2).

Table 1. Average weight gain (AWG), specific growth rate (SGR), feed conversion ratio (FCR) and survival of tilapias (Nile, red) and prawns in the tank-based experiments.

Treatment	TILAPIA (Nile or Red)				GIANT FRESHWATER PRAWN			
	AWG (g)	SGR (%/Day)	FCR	Survival (%)	AWG (g)	SGR (%/Day)	FCR	Survival (%)
				Wet Season (June 2020–October 2020)				
NileMONO	199.9 ^{a} (±32.6)	2.27 ^{a} (±0.12)	1.92	90.0 ^{a} (±5.0)				
NileCO	181.6 ^{a} (±25.2)	2.15 ^{a} (±0.1)	1.81	78.3 ^{a} (±14.2)	18.8 ^{a} (±3.1)	1.25 ^{a} (±0.11)	n.a. *	10.0 ^{b} (±1.9)
RedMONO	143.7 ^{a} (±9.2)	2.13 ^{a} (±0.4)	2.13	91.7 ^{a} (±1.7)				
RedCO	128.8 ^{a} (±14.9)	2.02 ^{a} (±0.12)	2.11	95.0 ^{a} (±2.9)	20.2 ^{a} (±2.8)	1.30 ^{a} (±0.06)	n.a. *	32.0 ^{a} (±14.6)
				Dry Season (February 2021–July 2021)				
NileMONO	239.4 ^{a} (±13.1)	2.89 ^{a} (±0.03)	1.81	75.0 ^{a} (±2.9)				
NileCO	213.1 ^{a} (±8.8)	2.79 ^{ab} (±0.01)	1.95	78.3 ^{a} (±1.7)	13.9 ^{a} (±0.3)	1.15 ^{b} (±0.05)	n.a. *	51.0 ^{b} (±1.0)
RedMONO	110.0 ^{b} (±11.1)	2.40 ^{b} (±0.11)	2.02	76.7 ^{a} (±8.8)				
RedCO	129.4 ^{b} (±10.5)	2.52 ^{b} (±0.05)	1.99	83.3 ^{a} (±3.3)	13.8 ^{a} (±1.98)	1.17 ^{a} (±0.15)	n.a. *	72.3 ^{a} (±10.1)

Means in the same column (consider runs separately) with different superscripts differ significantly ($p < 0.05$). Standard errors of the means are in parentheses; * n.a. = not applicable since prawns were unfed.

Table 2. Growth and survival of the I-Excel Nile tilapia, red tilapia and giant freshwater prawns in lake-based cage co-culture systems under different feeding schemes.

Treatment	Average Weight Gain (g)			Specific Growth Rate (%/day)			Survival (%)		
	Nile	Red	GFP	Nile	Red	GFP	Nile	Red	GFP
					Wet Season				
T_{fed}	247.3 ^{b} (±11.8)	180.3 ^{a} (±3.7)	32.3 ^{b} (±2.3)	2.66 ^{a} (±0.06)	2.50 ^{a} (±0.03)	1.42 ^{b} (±0.06)	54.7 ^{a} (±9.3)	78.7 ^{a} (±5.3)	50.6 ^{a} (±14.4)
GFP_{fed}	64.6 ^{c} (±4.7)	59.2 ^{b} (±1.2)	79.3 ^{a} (±7.4)	1.85 ^{b} (±0.04)	1.77 ^{b} (±0.0)	1.89 ^{a} (±0.06)	64.0 ^{a} (±16)	81.3 ^{a} (±3.5)	42.3 ^{a} (±15.3)
$T\text{-}GFP_{fed}$	276.0 ^{a} (±21.5)	173.5 ^{a} (±11.9)	65.0 ^{a} (±1.5)	2.77 ^{a} (±0.01)	2.43 ^{a} (±0.05)	1.85 ^{a} (±0.02)	45.3 ^{a} (±6.7)	56.0 ^{a} (±10.1)	62.2 ^{a} (±3.1)
					Dry Season				
T_{fed}	236.8 ^{a} (±6.9)	123.9 ^{a} (±1.6)	17.7 ^{a} (±0.05)	3.17 ^{a} (±0.02)	2.54 ^{a} (±0.01)	1.44 ^{b} (±0.0)	40.0 ^{a} (±4.0)	25.3 ^{a} (±9.6)	65.3 ^{b} (±0.9)
GFP_{fed}	60.6 ^{b} (±9.04)	45.5 ^{b} (±4.1)	32.7 ^{a} (±2.2)	2.16 ^{b} (±0.13)	1.90 ^{b} (±0.05)	1.91 ^{a} (±0.08)	52.0 ^{a} (±2.3)	41.3 ^{a} (±11.9)	65.0 ^{b} (±1.2)
$T\text{-}GFP_{fed}$	226.5 ^{a} (±22.1)	119.2 ^{a} (±6.5)	33.5 ^{a} (±1.3)	3.04 ^{a} (±0.05)	2.53 ^{a} (±0.05)	1.90 ^{a} (±0.02)	49.3 ^{a} (±13.5)	52.0 ^{a} (±12.2)	69.3 ^{a} (±1.2)

Means in the same column (consider runs separately) with different superscripts differ significantly ($p < 0.05$). Standard errors of the means are in parentheses.

3.2. Lake-Based Tilapia–Prawn Co-culture Feeding Management Trials

Tables 2 and 3 show the growth, survival and feed conversion ratios for the tilapias (I-ExCEL Nile and red) and giant freshwater prawns (GFP) reared in co-culture in lake-based net cages using different feeding protocols.

Table 3. Estimated feed conversion ratios in the tilapias and prawns reared in lake-based co-culture systems using different feeding schemes.

Treatment	Feed Conversion Ratio	
	Nile and Red Tilapia	Giant Freshwater Prawn
	Wet Season	
T_{fed}	1.57	n.a.
GFP_{fed}	n.a.	2.51
T-GFP_{fed}	1.83	2.79
	Dry Season	
T_{fed}	1.92	n.a.
GFP_{fed}	n.a.	3.65
T-GFP_{fed}	1.93	3.46

n.a. = not applicable; no artificial feeds were given.

Like in the tank co-culture experiment, whether fed or unfed, the I-ExCEL Nile tilapias grew better than the red tilapias when co-cultured with prawns in lake-based cages. In the wet season run, where a lower prawn stocking density was used, the growth of I-ExCEL Nile and red tilapias in treatment T_{fed} (AWG = 247.3 g, SGR= 2.66%/day and AWG = 180.3 g, SGR = 2.50%/day, respectively) were comparable with those in treatment T-GFP_{fed} (276 g, 2.77%/day and 173.5 g, 2.43%/day for the I-ExCEL Nile and red, respectively; Figure S3 in Supplementary material A). Red tilapia grew roughly 30% slower than I-ExCEL Nile, while their survival (56–81%) was noted to be higher than that of the I-ExCEL Nile tilapias (45–64%) in all the treatments (Figure S4 in Supplementary material A) for the wet season run. Feed conversion ratios were low for all the fed tilapias (1.57 and 1.83).

On the other hand, the prawns in treatment T_{fed} were half lighter (AWG = 32.3 g; although already considered locally as marketable size) than the prawns in GFP_{fed} and T-GFP_{fed} (79.3 g and 65.0 g, respectively; Table 3). Prawn survival in all the treatments did not differ significantly, ranging from 42.3–62.2%. It should be noted though that all species, especially the prawns, generally grew (in terms of average weight gain) better in the wet season run than those in the dry season run. The average weight gain of prawns in the wet season were twice heavier than the prawns in the dry season, and this could be attributed to the lower prawn stocking density in the wet season. Feed conversion ratios for the prawns in the wet season were higher (2.51, 2.79 for GFP_{fed} and T-GFP_{fed}, respectively) than the FCR for tilapias (1.57, 1.83 for the T_{fed} and T-GFP_{fed}, respectively).

In the dry season run, a similar trend in the growth of the tilapias was noted, although here, I-ExCEL Nile tilapias from treatment T_{fed}> grew slightly better, at 236.8 g AWG and 3.17%/day SGR (Figure S3 in Supplementary material A) than those from treatment T-GFP_{fed}. The red tilapias grew at half the size than the I-ExCEL Nile and survived poorly (25.3–52%) compared to those in the first run (56–81.3%) (Figure S4 in Supplementary material A). On the other hand, prawn survival was slightly higher (65–69.3%) compared to the first run, and since the stocking density in the second run was higher as well, prawns at final harvest were smaller (17.7 g to 33.5 g). Finally, mean feed conversion ratios for the prawns (3.46, 3.65 for the GFP_{fed} and T-GFP_{fed}, respectively) were also higher than those for tilapias (1.92, 1.93 for the T_{fed} and T-GFP_{fed}, respectively). One-way ANOVAs on I-ExCEL Nile tilapia growth (AWG) in relation to treatment (feeding protocol) for each season only showed significant treatment effects on growth (p = 0.002, p = 0.000) for each run. Meanwhile, for the red tilapias, an ANOVA on red tilapia growth had significant treatment (p = 0.000) effects (p = 0.010). For the prawns, treatment had significant effects on prawn growth (p = 0.000) for each season while survival percentages were not significantly different regardless of season.

3.3. Tank and Lake Water Quality and Natural Food Organisms in the Lake

3.3.1. Water Quality in the Rearing Tanks and Lake-Based Cages

Table 4 shows the water quality parameter measurements in the tank and lake facilities during the five-month trials. In the outdoor tanks, the physico-chemical parameters of the water during the entire culture period were still within tolerable limits for all the test species. However, it should be noted that the temperature range for run 2 (or during the dry season) in the outdoor tanks was rather wider than in run 1, meaning the extreme temperature readings had a difference of 6.1 °C (based on a range of 26.1–32.3 °C). The temperature lows were experienced in February and water temperature in outdoor concrete tanks can easily fluctuate, given that the water in the tanks is shallow. The warmest temperatures were noted in the peak of summer months, that is, from April to May. As for run 1, the temperatures were quite steady, ranging from 30.2 to 31.9 °C. Mean dissolved oxygen and pH readings were higher during run 2 than in run 1. Ammonia readings were likewise taken and ranged from 0 to 1 mg/L (Table 4).

Table 4. Summary of the water quality parameters noted in the two experimental areas for the duration of the study.

	Dissolved Oxygen (mg/L)		**Water Temperature(°C)**		**pH**		**Transparency (cm)**		**Ammonia Level (mg/L)**	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Tank experiment										
Wet season	4.7	3.3–6.4	30.9	30.2–31.9	6.5	5.6–7.7	–	–	0.5	0–1 *
Dry season	7.6	5.5–10.6	29.9	26.1–32.3	8.5	7.8–8.9	–	–	0.5	0–1 **
Lake experiment										
Wet season	5.3	3.7–7.7	30.9	29.9–32.4	6.1	5.3–6.7	61.8	57–70	0.125	0–0.25
Dry season	7.2	4.8–9.9	30.6	28.3–32.8	8.9	8.3–9.5	27.8	21.7–40	0.15	0–0.3 **

* ammonia level of 1 noted only twice in September 2020; ** ammonia level of 1 noted once in April 2021.

The basic physico-chemical parameters monitored in the lake were also within tolerable limits for growing the different test species. However, similar to what was observed in tanks, the dissolved oxygen and pH values in the lake were higher for the second run compared to the first run. Water transparency data were collected from the lake setup and the mean water transparency recorded for the second run was lower, at 27.8 cm, than that of the first run, at 61.8 cm.

3.3.2. Available Natural Food in the Lake

For the lake-based trials, water samples were taken not only for physico-chemical analysis but also for monitoring natural food organisms that are present in the cages. The following phytoplankton species have been recorded as thriving in the lake—three blue-green algal species (namely, *Microcystis* sp., *Lyngbya* sp., and *Anabaena*), three green algal species (*Pediastrum* sp., *Scenedesmus* sp. and *Spirogyra* sp.), two diatom species (*Melosira* sp. and *Cyclotella* sp.) and one dinoflagellate species (*Ceratium* sp.). Zooplanktons such as rotifers (*Brachionus calyciflorus*, *Keratella tropica*, *Monostyla* sp., *Lecane* sp. and *Filinia diaptomus*) have been noted as well, apart from small crustaceans such as copepods and cladocerans (*Moina macrocopa*, *Bosmina* sp. and *Daphnia* sp.). Of the various phytoplankton species, the blue-green algae *Microcystis* sp. was the most dominant, with mean cell densities ranging from 25.56 cells/mL to as high as 174.7 cells/mL, depending on the season and the physico-chemical conditions of the water in the eutrophic lake. The highest mean cell density of the blue-green algae *Microcystis* sp. In the lake cages during the wet season it was noted in September 2020 at 174.7 cells/mL, while the highest noted during the dry season was in July 2021 at 59.44 cells/mL (Figures S5 and S6 in Supplementary material A).

3.4. Feeding Efficiency Analysis

3.4.1. Tank Experiment, Wet and Dry Seasons

The fed tilapias were stocked in a cage within a concrete tank, while the unfed GFP were stocked directly in the tank outside the cage, as described earlier. Rearing runs were conducted during the wet and dry seasons. Feeds (25 kg sack packaging) that costs PhP 860 (USD 17.2; USD 1 = PhP 50) or PhP 34.40 (USD 0.68) per kg were used in the experiment. Figure 1a shows the average daily weight gain (g) per unit feed expenditure in Philippine perso (PhP) in the fed I-ExCEL Nile and red tilapia, while Figure 1b shows that for unfed GFP during the wet season. Figure 1a shows an increasing trend in the weight gain-per-unit feed expenditure in fed I-ExCEL Nile and Red tilapia in all four treatments from Periods 1 to 10. Within a period composed of 14 days between sampling, the highest weight gain-per-unit increase in feed expenditure were recorded for I-ExCEL Nile tilapias only, most prominently in Period 10, with a 9.09 g increase in daily weight per 1 PhP expenditure in feeds. Comparatively lower increment in weight-per-unit feed expenditure within a period was observed in Period 1 for the I-ExCEL Nile-GFP co-culture treatment, with only 3.19 g increase per unit of feed expenditure. For GFP, those stocked with I-ExCEL Nile were consistently higher than those for GFP stocked with red tilapia.

In contrast, the dry season tank setup had higher weight gain in fed I-ExCEL Nile and red tilapia for all four treatments during the preliminary period (P1 and P2), later showed a declining trend until P10, with some upward kinks in period P5 (Figure 1c). This suggests higher economic gains from feeding during the early grow out stages than in later stages during the dry season. In most of the periods, I ExCEL Nile tilapia reared singly showed the highest weight increase per unit feed expenditure, especially in P2 with 1.83 g. The weight gain-per-unit feed expenditure in GFP are all below 1.0 g in the dry season results (Figure 1d). GFP weight gain-per-unit feed expenditure is waning over the culture period until harvest. Overall, the efficiency of feeding is fairly not as improved during the dry season as compared to those in the wet season run.

3.4.2. Lake Experiment, Wet and Dry Seasons

For the lake setup during the wet season, Figure 2a shows a declining trend in the weight gain-per-unit expenditure of both I-ExCEL Nile and Red tilapia, although with an upward surge in Period 3, where weight gain-per-unit feed expenditure was 2.64 g/PHP. Computationally, the weight gain for Treatment Tilapia unfed + fed GFP returned an undefined value due to the zero value in the denominator for the feed applied. The weight gain-per-unit feed expenditure in GFP was mostly higher when both tilapia and GFP were fed (Figure 2b).

During the dry season, all treatments showed declining weight gain-per-unit feed expenditure on tilapia throughout from P1 to P10 (Figure 2c), although gains were higher for treatment fed Tilapia + unfed GFP than the treatment where both were fed. Similar declining trend are shown for treatment GFP fed + Tilapia unfed and treatment Both fed (Figure 2d). Overall, these trends show that feeding is most economically efficient during the early stages of the growing period during the dry season.

Figure 1. Weight gain-per-unit feed expenditure (g/PhP) in I-ExCEL Nile and red tilapia (fed) and GFP (non-fed) reared in tanks during the wet season (**a**,**b**) and dry season (**c**,**d**).

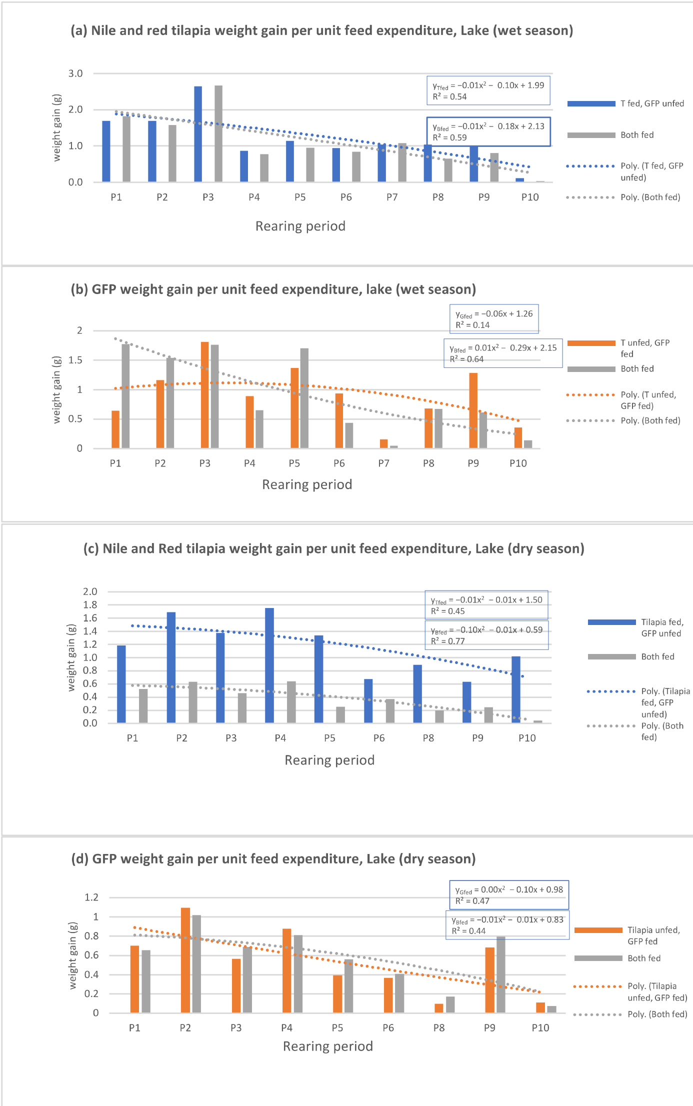

Figure 2. Weight gain-per-unit feed expenditure for fed and unfed I-ExCEL Nile and Red tilapia (**a**,**c**) and fed and unfed GFP (**b**,**d**) in cages in the lake setup, wet and dry season.

4. Discussion

4.1. Tilapia Monoculture vs. Tilapia–Prawn Co-Culture in Tanks

When grown in monoculture or in co-culture with the prawns in the outdoor concrete tanks, results, I-ExCEL Nile tilapias grew best to marketable sizes in five months compared to red tilapias, especially during the wet season regardless of the culture system. These results are quite similar to the results of a polyculture study but using another genetically improved Nile tilapia strain (GIFT) and red tilapia and reared with prawns in ponds with carbon/nitrogen controlled periphyton [21]. It should be noted that most of the tilapia–prawn co-culture research that have been conducted are those conducted in ponds as reviewed by New and Valenti [29]. It is therefore difficult to compare the results of this current research with earlier studies since the information generated herewith are based on novel culture systems (tanks and/or cages in lakes). Haque et al. [21] noted that the GIFT Nile tilapia had significantly higher individual weight gain, SGR, gross and net yields, FCR and survival as well as economic returns compared to the hybrid red tilapia. In their study, the good performance of the GIFT was attributed to its superior genetic background aside from social and behavioral interactions that favored their ability to compete for food [21]. Red tilapias, which are hybrids produced from crosses between Nile and Mozambique tilapia, are also known to grow better in brackish water and seawater conditions than in freshwater, which could probably explain why it has not shown optimal growth and survival in freshwater among other factors [19].

In the present study, apart from adequate nutrition from the artificial diet plus the water quality conditions (especially the stable mean water temperature of 30.9 °C) that favored good growth, I-ExCEL Nile tilapia grew better than the red hybrids even in cages within the tanks. As the I-ExCEL Nile tilapia was selectively bred for enhanced growth, it has been reported as having production traits even more superior than the GET ExCEL strain [13,22] (developed by BFAR in 2002) and perhaps even over the other GIFT-derived strains. Based on anecdotal reports from the Bureau of Fisheries and Aquatic Resources, which developed I-ExCEL [23], this strain was noted to have the ability to tolerate temperature fluctuations. In our study, the growth performance advantage of the I-ExCEL over the red tilapias was quite evident, especially in the second run where the AWG of the I-ExCEL was almost twice heavier than those of the red tilapias (Table 1). It was in the second run that the extreme temperature readings of the water in the tanks differed by about 6.2 °C (Table 4). However of course several adverse environmental factors, apart from innate hardiness or the lack thereof of the tilapia species used, could have contributed to the differences in the growth (AWG) of i-ExCEL vs. the red tilapias.

In terms of survival, the red tilapias survived slightly, but not significantly, better than the I-ExCEL Nile tilapia especially when co-cultured with the prawns. However, the prawns which were unfed, as expected, survived poorly. In tilapia–prawn polyculture in ponds, it is usually the tilapias that are fed. Prawns when reared unfed in earthen ponds together with caged fish, rely or feed on fish feces (coprophagy), natural food, benthic macroinvertebrates and detritus that accumulate on the sides and bottom of netcages [12]. However, in this case, during the wet season, natural food, if any, nor detritus (e.g., dying algal cells) may not have been sufficient for the prawns to thrive on due to minimal primary productivity brought about by poor photosynthetic activity during the rainy months. This apart from the fact that water in the tanks was fully changed once every two weeks. Moreover, the lower mean dissolved oxygen (4.7 mg/L, although still with the tolerable range [4]) in the wet season run compared to the dry season run (7.6 mg/L), among several other factors, could have resulted to poor prawn survival (10% and 32%). It should be remembered that growth and survival in prawns depend on numerous factors such as stocking density, feed, temperature, etc. [4]. For prawn production to be considered as satisfactory, prawn survival during the grow -out phase should not be below 50% [4].

On the other hand, the results of the dry season run were better than that of the wet season run considering most of the production traits (especially survival) in all the test species. This was true for the co-culture treatments where growth of the Nile tilapias (213.1 g AWG, 2.79%/day SGR) and survival of the prawns (51% and 72.3%) were higher than those for the first run. The prawns survived well, given the higher mean dissolved oxygen level (7.6 mg/L) in the rearing water and possibly due to better primary productivity during the dry months. However, Nile and red tilapia survival (75–83.3%) were slightly lower in the second run than what was noted in the first run in view of the wide temperature range (6.2 °C) experienced during the wet season. This notwithstanding, the survival percentages of the tilapias are still good enough in terms of yield.

Finally, based on our study, tilapia–prawn co-culture in tanks using low stocking densities of 10/m^2 and 7.5/m^2 for tilapias and prawns, respectively, can give good results particularly when reared under favorable water quality conditions. Since rearing is done in tanks, water quality parameters, if closely monitored and managed, may even further improve fish and prawn yield. On the whole, tilapia–prawn co-culture in tanks using I-ExCEL or especially when using red tilapias, could be economically feasible (apart from it being technically viable) given that two of the three test species used are high-value species, and hence could provide better monetary returns. This needs to be validated as yet through an economic analysis.

4.2. Tilapia–Prawn Co-Culture in Lake Cages

Prawn monoculture in lake cages have been demonstrated to work and could be a viable alternative to pond culture based on earlier studies [8,10] conducted in the same eutrophic lake, Laguna de Bay, where this present study was completed. Although the giant freshwater prawn *Macrobrachium rosenbergii* is not endemic in Laguna de Bay, its introduction in the lake for aquaculture does not have any adverse ecological impacts that most introduced species have caused. This prawn species could not complete its life cycle in the lake for it requires brackishwater for successful larval rearing which makes it ideal for lake-based cage farming. Cuvin-Aralar et al. [14,16] determined the stocking density and other culture parameters that could be suitable for lake-based prawn farming. They noted that the lower the stocking density for cage rearing of freshwater prawns, the significantly better are their growth and survival as well as overall proportion of larger prawns. Results of their study showed that the survival of prawns reared for five months ranged from 36.9–55.3%, where the highest survival was observed in the treatment with the lowest stocking density of 15 prawns/m^2 based on cage bottom dimensions. They tested stocking densities of 15, 30, 60 and 90/m^2. They noted that the feed conversion ratio improved as well with decreasing stocking density, that is from 2.1 to 3. In our study, the FCR of prawns reared in the lake was similar, with the lowest at 2.51 and the highest at 3.65 depending on the stocking density.

The effects of varying feeding treatments on the production traits of tilapias and prawns co-cultured in lake-based cages using lower stocking densities were evaluated in the current study. When tilapias (I-ExCEL Nile and red hybrids) were stocked together as primary commodities (at a total of 12.5/m^2) in larger-meshed cages set inside hapa net cages with the prawns (2.4/m^2 for the wet season trial and 4/m^2 for the dry season trial), it was shown that the results were quite variable. The growth and survival percentages of all test species were better when reared during the first run (wet season), when prawns were stocked at a lower density compared to the second run. In treatment T_{fed} where only tilapias were fed, tilapias grew at rates that are comparable with those where both tilapias and prawns were fed. More noteworthy is the result that, even when unfed, the prawns in treatment T_{fed} grew at the desired mean marketable size of 32.3 g AWG in five months. The other treatments where the prawns were fed, grew at double the size. Prawn survival at the low stocking density of 2.4/m^2 was at an average of 51.7% whether fed or unfed. This was well within the range of the observed survival rate noted by Cuvin-Aralar et al. [16] when they conducted prawn monoculture in the lake at densities ranging from 15/m^2 to 90/m^2, that is, from 36.9–55.3%, the lowest survival being noted for the 90/m^2 stocking density. The lowest stocking density in that study where prawns were also fed had FCR ranging from 2.1–3 [16]. In this present study, prawn FCR were similar given that the prawn stocking density used was very low. Primary productivity data collected during the trials showed that more available natural food especially blue-green algae e.g., Microcystis aeruginosa, and other planktonic organisms (rotifers, small crustaceans), were recorded during the latter part of the wet season. These natural food organisms (phytoplankton species for tilapias; phytoplankton, rotifers and crustaceans for the prawns) have supplemented the commercial diets that were administered to all the test species during the five-month lake-based rearing.

In the dry season run, red tilapia survival was lowest at 25.3% and ranged from 25.3–52% whether fed or not. Poor or low mean water transparency (27.8 cm) was noted during this rearing period. This, among other factors (abiotic or biotic, to include interaction with the Nile tilapia in the cages) could have affected red tilapia growth and survival [30,31] especially during the first few weeks of culture. Meanwhile, the prawns even when stocked at a higher density showed higher survival (65–69.3). However, since the number of prawns is higher, the mean size of the prawns at harvest were half the size of those obtained in run 1, and the FCR in the fed prawns were noted to be higher at 3.45–3.65. If this stocking density of 4/m^2 for prawns in the lake-based co-culture setup will be adopted or promoted, in spite the high FCR, selective harvesting can be done on the fourth month by first culling out the larger prawns and allowing the rest of the prawns (especially the orange clawed males and the runts) to grow to the desired sizes until the end of the entire rearing period.

4.3. Feeding Efficiency Economic Analysis

Overall, these experiments evaluating the different co-culture and feeding management schemes showed an increasing trend in fish biomass or weight gain-per-unit feed expenditure at the earlier stages of the grow-out period. This suggests a positive economic efficiency from feed utilization. Feeding both the I-ExCEL Nile and Red tilapia stocked in cages within a tank where unfed GFP are separately and directly stocked showed highest feeding efficiency because of the enclosed system and better survival rates especially for the tilapias. Mortalities are inevitable, as discussed in a separate section of this paper. However, when weight gain-per-unit feed expenditure declines even without mortalities, this indicates that additional feeding and corresponding expenditures are no longer providing economic returns. This is an indicator that harvesting could be an option, as economic benefits no longer outweigh costs. This analysis showed the importance of monitoring feeding efficiency especially in semi-intensive tank and lake-based co-culture systems where supplementary feeding is involved. Compared to pond-based tilapia–prawn co-culture/polyculture schemes, which apply several cost-effective management protocols such as biofloc technology [7], periphyton based systems, rice paddy culture systems or even in tilapia wastewater in settlement tanks [29], the co-culture schemes presented in this current study may still require further refinements, such as the use of farm-made feeds, optimal stocking densities and the formulation of management methods based on feeding efficiency analyses to make the system as economically efficient and/or viable.

5. Conclusions

Small-scale tilapia farmers operating low technology farms (e.g., backyard tanks and/or lake cage facilities) can adopt either tilapia monoculture or tilapia–prawn co-culture technologies based on (a) the priority and/or minor species, either tilapias or prawns, (b) target production traits (good growth, survival, FCR) and (c) the type of water quality management methods and other inputs applied in their grow-out system.

From the results of this study, given optimal water quality conditions, Nile tilapias (particularly genetically improved strains such as I-ExCEL) are best for both single-species farming and co-culture in freshwater outdoor concrete tanks. On the other hand, considering the performance of all the test species (I-ExCEL Nile tilapia, red tilapia and GFP) in the tanks, red tilapias stocked at $10/m^2$ in B-net cages (0.5–1 cm mesh size) set inside tanks with prawns ($7.5\ m/^2$ stocking density) can grow and survive well with prawns even when only the red tilapias are fed since the prawns grew and survive at rates higher than when these were co-cultured with the Nile tilapia. However, refinements in managing water quality (e.g., dissolved oxygen, water temperature, etc.) in the rearing enclosures should still be made. This can then help improve the growth performance of all the species used in co-culture while keeping in mind, also, the economic viability of the operations.

Although prawn growth was not quite optimal, tilapia–prawn co-culture in lake cages where only tilapias were fed (treatment T_{fed}) is still technically viable for fish farmers to adopt. Finally, results of the feeding efficiency analysis can serve as guide as well to when the different species (tilapias or prawns) should be harvested or when feeds are able to effectively contribute to the growth and survival of the farmed commodities.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su132413574/s1, Figure S1: Growth (SGR) of the different freshwater aquatic species (Nile tilapia, red tilapias, prawns) reared for five months using the cage-in-tank monoculture and/or co-culture schemes, Figure S2: Survival of all the freshwater aquatic species reared in the cage-in-tank monoculture and/or co-culture systems, Figure S3: Specific growth rates of the tilapias and prawns reared in lake-based co-culture systems using different feeding schemes, Figure S4: Survival of the co-cultured tilapias and prawns in the lake-based cages using different feeding protocols, Figure S5:

Results of plankton monitoring in the lake facility, wet season run, Figure S6: Results of plankton monitoring in the lake facility, dry season run

Author Contributions: Conceptualization, M.R.R.R.-E.; methodology, M.R.R.R.-E. and N.D.S.; formal analysis, M.R.R.R.-E. and N.D.S.; investigation, M.R.R.R.-E., M.P.R. and R.C.G.; data curation, M.P.R. and R.C.G.; writing—M.R.R.R.-E. and N.D.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded entirely by the Southeast Asian Fisheries Development Center Aquaculture Department (SEAFDEC/AQD) under study code: FS-01-2020B.

Institutional Review Board Statement: The study followed the SEAFDEC Aquaculture Department Institutional guidelines for the care, handling and use of the aquatic animals. Furthermore, no animals were sacrificed during the course of the study.

Informed Consent Statement: Not applicable.

Acknowledgments: The authors would like to thank Ma. Jodecel Danting, Head of the Bureau of Fisheries and Aquatic Resources National Freshwater Fisheries Technology Center (NFFTC) for facilitating the procurement of GET ExCEL Nile tilapia and giant freshwater prawn from their Center. We also thank Ryan Lazartigue and Joseph de la Cruz for their assistance in the conduct of the experiments. M.R.R.E also wishes to thank SEAFDEC/AQD for supporting her participation in the 8th International Conference on Fisheries and Aquaculture (ICFA2021) where the results of this research study was orally presented.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. FAO. The Impact of COVID-19 on Fisheries and Aquaculture Food Systems, Possible Responses: Information Paper, November 2020. Rome. 2021. Available online: https://www.fao.org/3/cb2537en/CB2537EN.pdf (accessed on 6 October 2021).
2. FAO. The Effect of COVID19 on Fisheries and Aquaculture in Asia. Bangkok. 2020. Available online: https://www.fao.org/3/ca9545en/CA9545EN.pdf (accessed on 6 October 2021).
3. New, M.B.; Kutty, M.N. Chapter 17. Commercial Freshwater Prawn Farming and Enhancement around the World. In *Freshwater Prawns. Biology and Farming*; New, M.B., Valenti, W.C., Tidwell, J.H., DÁbramo, L.R., Kutty, M.N., Eds.; Wiley-Blackwell Publishing: London, UK, 2009; pp. 346–399.
4. New, M.B. *Farming Freshwater Prawns. A Manual for the Culture of the Giant River Prawn (Macrobrachium rosenbergii)*; FAO Fisheries Technical Paper. No. 428; FAO: Rome, Italy, 2002; 212p.
5. Kutty, M.N.; Nair, C.M.; Salin, K.R. Freshwater prawn farming and its sustainability in South Asia. *World Aquac. Mag.* **2009**, *40*, 48–52, 68.
6. Zimmerman, S.; Nair, C.M.; New, M.B. Chapter 11. Grow-out Systems—Polyculture and Integrated Culture. In *Freshwater Prawns. Biology and Farming*; New, M.B., Valenti, W.C., Tidwell, J.H., DÁbramo, L.R., Kutty, M.N., Eds.; Wiley-Blackwell Publishing: London, UK, 2009; pp. 195–217.
7. Hisano, H.; Barbosa, P.T.L.; Hayd, L.A.; Mattioli, C.C. Evaluation of Nile tilapia in monoculture and polyculture with giant freshwater prawn in biofloc technology system and in recirculation system. *Int. Aquat. Res.* **2019**, *11*, 335–346.
8. Garcia-Perez, A.; Alston, D.E. Yield of freshwater prawn *Macrobrachium rosenbergii* (Decapoda) after removing its females from a continuous polyculture system with tilapia (Pisces) in Puerto Rico. *J. Agric. Univ. P. R.* **2009**, *93*, 69–82.
9. Bureau of Fisheries and Aquatic Resources. *Philippine Fisheries Profile 2019*; Department of Agriculture-Bureau of Fisheries and Aquatic Resources: Quezon City, Philippines, 2020; p. 76. Available online: https://bfar.da.gov.ph/publication.jsp?1d=2375#post (accessed on 6 October 2021).
10. Romana-Eguia, M.R.; Eguia, R.V.; Pakingking, R.V., Jr. *Tilapia Culture: The Basics*; Aquaculture Extension Manual 66; Aquaculture Department, Southeast Asian Fisheries Development Center: Iloilo, Philippines, 2020; 54p.
11. The Tilapia Technical Committee. *The Philippines Recommends for Tilapia*; PCAARRD Philippines Recommends Series No. 97/2016; Department of Science and Technology (DOST), Philippine Council for Agriculture, Aquatic and Natural Resources Research and Development (PCAARRD): Laguna, Philippines, 2018; 162p.
12. Romana-Eguia, M.R.; Laron, M.A.; Catacutan, M.R. On farm feed management practices for Nile tilapia (*Oreochromis niloticus*) in the Philippines. In *On-Farm Feeding and Feed Management in Aquaculture*; Hasan, M.R., New, M.B., Eds.; FAO Fisheries and Aquaculture Technical Paper No. 583; Food and Agriculture Organization: Rome, Italy, 2013; pp. 131–158.
13. Hamilton, M.G.; Lind, C.E.; Barman, B.K.; Velasco, R.R.; Danting, M.J.C.; Benzie, J.A.H. Distinguishing between Nile tilapia strains using a low-density single-nucleotide polymorphism panel. *Front. Genet.* **2020**, *11*, 594722. [CrossRef] [PubMed]
14. Cuvin-Aralar, M.L.A.; Lazartigue, A.G.; Aralar, E.V. Net mesh size affects production of giant freshwater prawn *Macrobrachium rosenbergii* cultured in lake-based cages. *J. Appl. Ichthology* **2013**, *29*, 833–838. [CrossRef]

15. Cuvin-Aralar, M.L.A.; Laron, M.A.; Aralar, E.V.; De la Paz, U. *Breeding and Seed Production of the Giant Freshwater Prawn (Macrobrachium rosenbergii)*; Aquaculture Extension Manual 52; Aquaculture Department, Southeast Asian Fisheries Development Center: Iloilo, Philippines, 2011; 33p.
16. Cuvin-Aralar, M.L.A.; Aralar, E.V.; Laron, M.A.; Rosario, W. Culture of *Macrobrachium rosenbergii* (De Man 1879) in experimental cages in a freshwater eutrophic lake at different stocking densities. *Aquac. Res.* **2007**, *40*, 181–187. [CrossRef]
17. Romana-Eguia, M.R.R.; Aralar, M.L.C.; Dejarme, H.; Rosario, W.R.; Tayamen, M.M. Genetic characterization, domestication and improvement of *Macrobrachium rosenbergii* in the Philippines. In *Recent Developments in the Genetic Improvement of the Giant Freshwater Prawn (Macrobrachium sp). A Compendium of Results from the Collaborative Prawn Genetic Improvement and Seed Production Research Project under the Program on the Promotion of Sustainable Aquaculture in the ASEAN Region (2002–2007)*; Eguia, M.R.R., Aralar, M.L.C., Eds.; Compilers; Government of Japan Trust Fund; SEAFDEC; Association of Southeast Asian Nations: Southeast Asian Fisheries Development Center, Aquaculture Department: Iloilo, Philippines, 2007; 86p.
18. Tambalque III, H.S.; Perez, M.L.; Nieves, P.M.; Corre, V.L.; Duarte, J.A.; Pulido, N.A.; Dejarme, H.E.; Tanay, D.; Garces, L.R. Challenges and opportunities for giant freshwater prawn culture through participatory learning and fish farmer engagements. *Asian J. Agric. Dev.* **2015**, *12*, 35–52.
19. Romana-Eguia, M.R.R.; Eguia, R.V. Growth of five Asian red tilapia strains in saline environments. *Aquaculture* **1999**, *173*, 161–170. [CrossRef]
20. Lingam, R.S.S.; Kumar, J.S.S.; Chidambaram, P.; Aanand, S.; Velmurugan, P.; Venkatrao, B.R. An insight to red tilapia breeding and culture: A farmer advisory. *Aquac. Asia* **2021**, *25*, 21–26.
21. Haque, M.R.; Islam, M.A.; Wahab, M.A.; Hoq, M.E.; Rahman, M.M.; Azim, M.E. Evaluation of production performance and profitability of hybrid red tilapia and genetically improved farmed tilapia (GIFT) strains in the carbon/nitrogen controlled periphyton-based (C/N-CP) on-farm prawn culture system in Bangladesh. *Aquac. Rep.* **2016**, *4*, 101–111. [CrossRef]
22. Tayamen, M.M. Nationwide dissemination of GET ExCEL Tilapia in the Philippines. In Proceedings of the Sixth International Symposium on Tilapia in Aquaculture, Manila, Philippines, 12–16 September 2004; Bolivar, R., Mair, G., Fitzsimmons, K., Eds.; Bureau of Fisheries and Aquatic Resources: Quezon City, Philippines, 2004; Volume 1, pp. 74–88.
23. Bureau of Fisheries and Aquatic Resources—National Freshwater Fisheries Technology Center. *Improved GET ExCEL 2016. Brochure*; Department of Agriculture-Bureau of Fisheries and Aquatic Resources: Quezon City, Philippines, 2016; p. 1.
24. Uddin, M.S. Mixed Culture of Tilapia (*Oreochromis niloticus*) and Freshwater Prawn (*Macrcobrachium rosenbergii*) in Periphyton-Based Ponds. Ph.D. Thesis, Fish Culture and Fisheries Group, Wageningen University, Wageningen, The Netherlands, 2007; 215p.
25. Thongrod, S. Analysis of feeds and fertilizers for sustainable aquaculture development in Thailand. In *Study and Analysis of Feeds and Fertilizers for Sustainable Aquaculture Development*; Hasan, M.R., Hecht, T., De Silva, S.S., Tacon, A.G.J., Eds.; FAO Fisheries Technical Paper No. 497; FAO: Rome, Italy, 2007; pp. 309–330. 510p.
26. Danaher, J.J.; Tidwell, J.H.; Coyle, S.D.; Dasgupta, S.; Zimba, P.V. Effects of two densities of caged monosex Nile tilapia *Oreochromis niloticus* in cages on water quality, phytoplankton populations and production when polycultured with *Macrobrachium rosenbergii* in temperate ponds. *J. World Aquac. Soc.* **2007**, *38*, 367–382. [CrossRef]
27. Tidwell, J.H.; Coyle, S.D.; Bright, L.A. Polyculture of Nile tilapia, *Oreochromis niloticus*, either confined in cages or unconfined in freshwater prawn, *Macrobrachium rosenbergii*, ponds. *J. World Aquac. Soc.* **2010**, *41*, 616–625. [CrossRef]
28. Wilkinson, L.; SYSTAT. *The System for Statistics*; SYSTAT Inc.: Evanston, IL, USA, 1987.
29. New, M.B.; Valenti, W.C. Chapter 11. Tilapia-Macrobrachium Polyculture. In *Tilapia in Intensive Co-Culture*, 1st ed.; Perschbacher, P.W., Stickney, R.R., Eds.; John Wiley and Sons Ltd.: Hoboken, NJ, USA, 2017; pp. 156–187.
30. Makori, A.J.; Abuom, P.O.; Kapiyo, R.; Anyona, D.N.; Dida, G.O. Effects of water physico-chemical parameters on tilapia (*Oreochromis niloticus*) growth in earthen ponds in Teso North Sub County, Busia County. *Fish. Aquat. Sci.* **2017**, *20*, 30. [CrossRef]
31. El-Sayed, A.-F.M. Chapter 4. Environmental requirements. In *Tilapia Culture*, 2nd ed.; Academic Press: Cambridge, MA, USA, 2020; pp. 47–62.