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Comparative Study on the Productive and Economic Performance of *Litopenaeus vannamei* and *Oreochromis niloticus* in Monoculture and Polyculture Systems in Egypt

Abd El Rahman A. Khattaby[1*], Asmaa S. Abd El-Naby[2], Faatima H. Abozaid[3], Reham M. Fawzy[2], Eman Antar[1]

[1]Fish Production and Aquaculture Systems Research Department, Central Laboratory for Aquaculture Research, Agriculture Research Center, Egypt
[2]Fish Nutrition Department, Central Laboratory for Aquaculture Research, Agriculture Research Center, Egypt
[3]Fisheries Division, National Institute of Oceanography and Fisheries, Egypt
***Corresponding author:** AbdElRahman.Khattaby@arc.sci.eg, a.a.khattaby@gmail.com

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ABSTRACT

Tilapia ranks as the second most cultivated fish species globally, with production having more than quadrupled in recent years due to ease of farming, high consumer demand, and stable market prices. To support continued growth and enhance sustainability, tilapia farming should adopt more sustainable practices such as polyculture systems. One such practice—integrating tilapia with shrimp—has been successfully applied by farmers in Egypt, yielding promising results in terms of overall farm productivity and operational efficiency. This study was conducted in Al-Hamoul, Kafr El-Sheikh Governorate, Egypt, to evaluate water quality, growth performance, feed conversion efficiency, and economic viability of the Nile tilapia **(***Oreochromis niloticus***)** and Pacific white shrimp **(***Litopenaeus vannamei***)** in monoculture and polyculture systems. Three production cycles were carried out, each with three replications. The experimental treatments included: tilapia monoculture **(**TM**)** with 100 tilapia per tank, shrimp monoculture **(**SM**)** with 250 shrimp per tank, in addition to tilapia-shrimp polyculture **(**TSP**)** with 100 tilapia and 250 shrimp per tank. Both species were fed experimental diets containing 30% crude protein and 7% crude fat, administered to apparent satiety three times daily at 08:00, 11:00, and 14:00 over a 120-day period, under water salinity conditions of 10ppt. Water quality parameters—including temperature, dissolved oxygen **(**DO**)**, salinity, unionized ammonia, and pH—were regularly monitored. Growth performance, feed utilization, and survival rates were assessed at the end of the experiment. Water quality remained within optimal ranges for both species. Results indicated that integrating shrimp into tilapia farming did not negatively impact tilapia yield and may have positively influenced growth performance and survival rates. Feed utilization parameters showed no significant differences between monoculture and polyculture systems. Furthermore, the polyculture system demonstrated improved economic performance and productivity compared to monocultures.

INTRODUCTION

Aquaculture activities must be planned based on the concept of sustainability, incorporating the responsible exploitation of biological resources and the social benefits they generate **(Valenti**

***et al.*, 2010)**. In this context, aquaculture is a rapidly growing industry that plays a crucial role in meeting the increasing global demand for seafood. However, traditional methods often face challenges such as limited water resources, wastewater discharge, and disease outbreaks. Polyculture systems align with the principles of sustainable aquaculture and have received considerable attention for their potential to enhance productivity while minimizing environmental impacts **(Martinez-Porchas *et al.*, 2010)**.

One promising system is the combination of tilapia **(***Oreochromis niloticus***)** and whiteleg shrimp (*Litopenaeus vannamei*), known as tilapia–shrimp polyculture **(Cristiano *et al.*, 2023)**. Polyculture techniques have been implemented in various commercial aquaculture systems. Among control farms in Egypt, 59% practice the polyculture of the Nile tilapia, carps, and mullets **(Nabil *et al.*, 2006; Dickson *et al.*, 2016; Shaalan *et al.*, 2018; Abdel-Tawwab *et al.*, 2019)**. These systems improve water quality, control phytoplankton growth, reduce organic matter in effluents, and help prevent disease outbreaks in tilapia and shrimp **(Ye *et al.*, 2011; Fitzsimmons & Shahkar, 2017)**.

The polyculture or co-culture of shrimp and tilapia has been tested in various locations in recent years to assess production yield and efficiency **(Martinez-Porchas *et al.*, 2010; Yuan *et al.*, 2010; Shahin *et al.*, 2011; Bessa Junior *et al.*, 2012; Juarez-Rosales *et al.*, 2020)**. Tilapia and shrimp have complementary ecological requirements, feeding behaviors, and growth patterns that make their co-cultivation mutually beneficial **(Macfadyan *et al.*, 2011)**.

Combining tilapia and shrimp in polyculture ponds provides several benefits. First, it optimizes resource use by exploiting different trophic levels within the ecosystem **(Selvin, 2010)**. The Nile tilapia is considered the "queen of fish" in Egypt and Africa due to its importance as a protein source and its affordability and availability **(Ammar *et al.*, 2021)**. Tilapia predominantly feed on detritus and plankton, minimizing nutrient build-up in the aquatic environment, while shrimp tolerate a range of salinities, grow rapidly, and have high market value **(Abd El-Naby *et al.*, 2024)**. Shrimp primarily consume natural food sources such as small crustaceans **(Pawar *et al.*, 2018)**. This complementary feeding behavior reduces competition for resources and boosts overall system productivity **(Gamboa-Delgado *et al.*, 2020)**.

Furthermore, the presence of tilapia helps mitigate water quality issues. Their continuous grazing on phytoplankton reduces the risk of algal blooms, ensuring adequate oxygen levels for both species. In addition, tilapia feed on parasite-carrying organisms, aiding in the control of diseases commonly affecting shrimp and reducing the reliance on antimicrobials and chemical treatments **(Khattab *et al.*, 2001)**. Tilapia can be successfully cultivated in brackish water and are widely tolerated in integrated systems in Egypt.

However, successful implementation of tilapia–shrimp polyculture requires a comprehensive understanding of species-specific needs, appropriate stocking densities, feed management, water quality control, and disease prevention. Effective management practices and continuous monitoring are essential to ensure the economic viability, ecological sustainability, and productivity of polyculture systems **(Cristiano *et al.*, 2023)**.

MATERIALS AND METHODS

Water quality parameters

A portable oxygen meter (970 portable DO meter, Jenway, London, UK) was used to measure the water temperature and dissolved oxygen onsite daily. A pH meter (Digital amaini-pH Meter, model 55, Fisher Scientific, Denver, CO, USA) was used to measure the daily pH. Water samples were subsequently taken weekly to monitor the unionized ammonia of total ammonia (NH3). The temperature, dissolved oxygen (DO) content, salinity, unionized ammonia content and pH were measured *in situ* in all the treatments between 8:00 and 9:00 am at medium depths. The total salinity of the water was 10ppm during all the experimental periods.

Experimental design

The trial was conducted via a completely randomized design consisting of three treatments with three replications for each. The first treatment included tilapia monoculture (TM) (100 tilapia/tank), the second treatment included shrimp monoculture (SM) (250 shrimp/tank), and the third treatment included tilapia-shrimp polyculture (TSP) (100 tilapia+ 250 shrimp/tank). The experiment lasted for 120 days. The total experimental tanks were nine rectangular concrete tanks (3 × 8 × 1m), with a water depth of 0.8m and a total water volume of 19 m/each tank. Each concrete tank was supplied with well-aerated water. Approximately 10% of the water in the tank was exchanged daily for waste removal, with a total amount of well water. At the end of the experiment, the concrete tanks were drained with siphon pipes. The tilapia and shrimp in each tank were collected from harvesting pits.

Experimental fish management

White shrimp (*Litopenaeus vannamei*) PL12 were purchased from a commercial hatchery located in Damietta, Egypt. The shrimp were transported to the farm and acclimated to reduce the water salinity from 25 ppm to 10 ppm at the target farm. After this, the shrimp were reared to grow to 7 grams. All Nile tilapia (*Oreochromis niloticus*) fry (5±0.2g) were transported from a commercial hatchery in Kafr El-Sheikh, Egypt. The tilapia were reared to 20 grams. The tilapia were acclimated from fresh water to 10 ppm salinity according to the target farm.

Fish and shrimp were reared in concrete tanks aerated by rootblowers and acclimated to farm conditions for one week, where they were fed a commercial diet containing 30% crude protein and 7% crude fat. The feed was 50% floating 50% sinking feed for the polyculture tanks, 100% fluting with the tilapia monoculture tanks, and 100% sinking with the shrimp monoculture tanks. After acclimatization, the fish were distributed inside 100 tilapia/tank and 250 shrimp/tank concrete tanks. The fish were hand-fed the assigned experimental diet up to apparent satiation three times daily at 08:00, 11:00 and 14:00 h. During the experiment, animal samples were taken every two weeks between 8:00 and 11:00 am. The animals were fished with nets from each tank, and the tilapia and shrimp were weighed and returned immediately.

Evaluation of growth performance and feed utilization efficiency

At the end of the feeding trial, the fish and shrimp were harvested, counted, and group-weighted per tank. The indices of growth and feed utilization were calculated as follows:

Weight gain = W2 – W1;

Relative body weight gain (%) = 100 (W2 – W1)/W1;

Specific growth rate (SGR; %g/day) = 100 (Ln W2 - Ln W1)/T;

where W1 and W2 are the initial and final fish weights (g), respectively, and T is the feeding trial period in days.

FI = total feed intake per tank/number of fish;

Feed conversion ratio (FCR) = feed intake (g)/body weight gain (g);

Protein intake (PI) = feed intake (g) × percent protein in the diet;

Protein efficiency ratio (PER) = weight gain (g)/total protein intake;

Fish survival (%) = 100 (final number of fish/initial number of fish).

Proximate analysis of diet

Proximate chemical components of the diets at the beginning of the experiment were determined in triplicate according to methods of the Association of Official Analytical Chemists **(AOAC, 2005)**. The moisture content was estimated by drying the samples in an oven at 105°C until a constant dry weight was achieved. The nitrogen content was measured with a micro-Kjeldahl apparatus, and the crude protein content was estimated by multiplying the total nitrogen content by 6.25. The total lipid content was determined by means of ether extraction for 16h, and ash content was determined by combusting samples in a muffle furnace at 550°C for 6h. Crude fiber content was estimated according to the method of **Goering and van Soest (1970)**. The gross energy was calculated as 16.7 kJ/g, 37.4 kJ/g, and 16.7 kJ/g for protein, lipids, and carbohydrates, respectively, according to the methods of the **National Research Council (2011)**.

Economic evaluation

Quantitative analysis methods such as financial evaluation criteria and economic feasibility studies were used. Additionally, the data envelopment analysis (DEA) approach was used to measure the economic and technical efficiency of the fish farms, and descriptive statistics were used to evaluate administrative efficiency.

The following are the most important laws and indicators that were used:

The total coasts were calculated via the following equation:

Total costs (US$) = feed cost (US$) + fish fry cost (US$) + operation cost (US$)

where feed cost (US$) = FI (g/fish) * feed price (US$/kg)

Fish seeds (Fries/fingerlings) cost (US$) = No. of seeds * Price of fish seeds (US$/1000 fry/fingerling)

Operation costs including labor salaries, power, and services

All experimental diet costs, fish fry costs and operation costs were calculated according to the prices in the Egyptian market during the study period.

The economic evaluation calculated via the following equation

Net income (US$) = Total fish price (US$) - Total costs (US$)

where Total fish price (US$) = ∑ fish weight of each grade (kg) * Fish price of each grade (US$/kg)

Fish weight of grade (kg) = total fish weight (kg) * % of fish grade

% income to cost = 100 *(Net income/total cost)

Criteria for financial evaluation of project feasibility studies

These criteria are divided into nondiscounted criteria and discount criteria as follows:

1. **Undiscounted criteria**

   - Payback period = (investments/total profit)
   - Operating ratio %= (total cost/total revenue).
   - Revenue on cost= (total revenue/total cost).
   - Return on investment%= (net profit/investment)
   - Return on revenue%= (net profit/revenue)

2. Discounting criteria

- Internal rate of return= Smaller discount rate + Difference between discount rates × (Smaller discount rate at additional net cash flow current value)/(Discount price at additional net cash flow current values between the absolute difference).

Statistical analysis

The results are presented as the means ± SEs of three replicates. The mean values for all monitored parameters were analyzed via one- and two-way ANOVA to assess the water quality, growth rate, feed utilization, and economic efficiency of the Nile tilapia (*Oreochromis niloticus*) and Pacific white shrimp (*Litopenaeus vannamei*) in monoculture and polyculture. Statistical significance was established at a threshold of $P< 0.05$ when compared via Duncan's multiple range tests. All the statistical analyses were carried out via SPSS software, SPSS, version 20.0. (SPSS, Richmond, VA, USA) according to **Dytham (2011)**.

RESULTS

Water quality parameters

Water quality parameters were compared by examining the overall average values at the end of the experimental period, and they were not significantly affected by the density or size of the tilapia-shrimp stock. All water quality parameters, such as temperature, pH, salinity, dissolved oxygen (DO) and total ammonia, were measured and recorded during the culture period from May to October, as shown in Table (1). In general, the temperatures during the treatment period ranged between 26.8°C, the lowest degree, and 28°C, the highest degree. The data indicated that the highest temperature occurred during August, when it reached 28°C in the shrimp and tilapia treated with the monoculture system. However, in the polyculture system, it was 27.9°C. Optimum temperatures for tilapia and very good temperatures for *L. vannamei* shrimp. These findings agree with those of **Enas Said *et al.* (2020)**, who noted that the optimum water temperature for Nile tilapia is approximately 28°C, as it enhances body weight and swimming behavior and reduces aggressive, surface, and scratching behavior. **Fernando *et al.* (2013)** further reported that the optimum water temperature for *L. vannamei* is between 27–29°C, promoting the best growing conditions in controlled environments.

The pH ranged from 7.4 to 7.6, which is ideal for tilapia and shrimp aquaculture. This approximate stability may be due to the dependence on well water, which is characterized by significant chemical quality stability. Similarly, **Hernadez-Barraza *et al.* (2012)** reported that the pH was between 7.1 and 7.6, whereas the mean temperature was 28.5°C.

For dissolved oxygen (DO), the lowest value was (6.3ppt) in October, and the highest value was (7.2 ppt). The stability of the value of dissolved oxygen throughout the experimental period was due to the dependence on changing the water directly, and the oxygen values are suitable for the growth of aquatic tilapia and vanamei shrimp.

The salinity of the water was measured to ensure that it did not fluctuate throughout the experimental period, as it was constant throughout the experimental period (10ppt), and since the water was well water, one of its properties was the stability of chemical qualities such as salinity, which is a ratio suitable for breeding tilapia and shrimp. **Dawood *et al.* (2023)** reported that the Nile tilapia can grow well in saltwater (5–10 parts of salinity), but high salinity (15ppm) combined with constant exposure to ammonia can impair their productivity and health status. **Mirera (2023)** reported that the Nile tilapia (*Oreochromis niloticus*) can adapt to seawater salinity levels of up to 30%, with successful growth rates when fed different diets, demonstrating the potential for marine aquaculture. Numerous studies indicate that *L. vannamei* shrimp can live in 10 ppt salt, which **Bückle *et al.* (2013)** studied the ability of *L. vannamei* shrimp live at different salinities at different temperatures and that *L. vannamei* shrimp can live at 10ppt salinity well at a water temperature of 28°C.

The concentration of total ammonia ranged between 0.9 and 0.5mg L^{-1}. The measured proportions of total ammonia in this study were within the safe limits for tilapia and shrimp. Many levels of ammonia are not affected by the breeding system or the species in the tanks, where the basin water is changed periodically to maintain the characteristics of water quality. Similarly, **Hernadez-Barraza *et al.* (2012)** reported that the concentration of total ammonia ranged from 0.10 to 0.14mg L^{-1}.

Water quality parameters remained within suitable ranges for optimal tilapia and shrimp cultivation. Most recent research on tilapia–shrimp cocultures have been carried out in tanks controlled in some physical and chemical variables **(Hernandez--Barraza *et al.*, 2012; Simao *et al.*, 2013; Lopez--Gomez *et al.*, 2017)**. The water quality variables during all farming cycles were within suitable range for tilapia and shrimp farmed in mono and coculture **(Candido *et al.*, 2005)**.

Table 1. Water quality variables in monocultures (tilapia and shrimp) and polycultures (tilapia/shrimp) during the summer months for 120 days

	Temperature (Cº)			Ph			Oxygen (mg/L)			Salinity (PPT)			Total Ammonia		
Months	**Tilapia Mono-culture**	**Shrimp Mono-culture**	**Tilapia/ Shrimp Poly Culture**	**Tilapia Mono-culture**	**Shrimp Mono-culture**	**Tilapia/ Shrimp Poly Culture**	**Tilapia Mono-culture**	**Shrimp Mono-culture**	**Tilapia/ Shrimp Poly Culture**	**Tilapia Mono-culture**	**Shrimp Mono-culture**	**Tilapia/ Shrimp Poly Culture**	**Tilapia Mono-culture**	**Shrimp Mono-culture**	**Tilapia/ Shrimp Poly Culture**
May	26.9	26.8	26.8	7.5	7.5	7.4	7.0	7.2	7.0	10	10	10	0.5	0.5	0.5
Jone	26.8	26.	26.7	7.4	7.5	7.5	6.9	6.8	7.0	10	10	10	0.7	0.5	0.9
July	27.5	27.3	27.5	7.4	7.4	7.5	7.0	6.8	6.9	10	10	10	0.9	0.7	0.7
August	28	28	27.9	7.5	7.5	7.4	6.8	6.6	6.9	10	10	10	0.8	0.8	0.8
September	27.1	27.2	27	7.6	7.5	7.5	6.8	6.6	7.0	10	10	10	0.7	0.7	0.8
October	27	27	27	7.4	7.4	7.4	6.8	6.3	6.9	10	10	10	0.6	0.8	0.9

2- Growth performance parameters

Tilapia in monoculture and polyculture

The growth performance of tilapia in both monoculture and polyculture systems is presented in Table (2). Comparisons of final weight (g), weight gain (%), relative body weight gain (RBWG), and specific growth rate (SGR, %/day) showed no significant differences ($P > 0.05$) between the monoculture and polyculture systems. These findings suggest that the presence of shrimp in polyculture did not negatively impact the growth performance of tilapia.

According to the data in Table (2), tilapia in monoculture reached a mean final weight of 280.76g, which was significantly higher than the 271.18g recorded in the polyculture group. However, the SGR values were very similar: 2.98%/day in monoculture and 2.95%/day in polyculture, indicating only minimal variation. This slight difference may be attributed to the non-competitive behavior of tilapia in polyculture, as well as their agility compared to shrimp, which might limit interspecies interference during feeding.

Tilapia is considered a strong candidate for polyculture with shrimp due to its tolerance to suboptimal environmental conditions, omnivorous feeding habits, and high commercial demand **(Martinez-Porchas *et al.*, 2010)**. **Yuan *et al.* (2010)** found that tilapia–shrimp polyculture is technically feasible, economically viable, and environmentally sustainable, particularly when appropriate feeding strategies are employed. Similarly, **Junior *et al.* (2012)** reported that shrimp–tilapia polyculture systems did not adversely affect fish production.

Throughout the feeding period, tilapia appeared to be in good health, as indicated by their general activity and behavior. No significant difference ($P > 0.05$) was observed in survival rates between culture systems, with survival ranging from 94 to 100% (Table 2). Interestingly, survival was slightly better in the polyculture system, possibly due to the more diverse environment created by the presence of both species. This diversity may influence the microbial and parasitic communities in a way that reduces the presence of harmful pathogens.

The observed survival rates are consistent with the findings of **Junior *et al.* (2012)**, who reported no significant differences in tilapia survival between different culture systems. The high survival rates in this study suggest that management practices were effective and that water quality remained within optimal parameters throughout the experiment.

Shrimp in monocultures and polycultures

The growth performance of shrimp in both monoculture and polyculture systems is summarized in Table (3). There were no significant differences in shrimp growth performance—final weight (g), weight gain (%), relative body weight gain (RBWG), and specific growth rate (SGR, %/day)—between the two systems. At the end of the 120-day trial, shrimp in the monoculture system reached an average final weight of 21.0g, which was slightly but significantly higher than the 20.75g recorded in the polyculture system. The SGR values were nearly identical: 3.06%/day in monoculture and 3.05%/day in polyculture.

The results also showed no significant differences in tilapia survival rates between the culture systems. Tilapia survival in monoculture was 99%, compared to 91% in polyculture. This slight decrease in polyculture could be attributed to interactions with shrimp during early molting stages, potentially affecting shrimp survival and performance.

Despite these minor differences, polyculturing shrimp with tilapia did not negatively impact tilapia yield and may offer additional benefits for growth and survival. The final weight, weight gain, and RBWG of tilapia were not significantly different between the systems, supporting the viability of integrated farming.

Compared with shrimp monoculture, integrating tilapia into shrimp rearing ponds has been shown to improve water quality, sediment condition, and overall shrimp production **(Fitzsimmons & Shahkar, 2017)**. Studies on tilapia–shrimp co-culture have investigated various factors such as stocking density **(Cândido *et al.*, 2005)**, water quality **(Alam *et al.*, 2008; Brito *et al.*, 2017)**, feeding strategies **(Jatobá *et al.*, 2011)**, and growth performance **(Hernández-Barraza *et al.*, 2012)**. **Yi *et al.* (2004)** also reported that the average final weight of shrimp did not differ significantly between monoculture systems and mixed-species, low-density or high-density co-cultures involving tilapia and shrimp in Thailand.

Table 2. Growth performance parameters of tilapia in monoculture and polyculture cultures during the summer months for 120 days

Means with the same letter in the same row are not significantly different at $P < 0.05$.

Tilapia	Growth performance					
	Initial weight (g)	Final weight (g)	Weight gain (g)	RBWG (%)	SGR (%/day)	Survival (%)
Mono-culture	22.91±0.15	280.76±4.68	257.85±4.60	1125.11±17.19	2.98±0.02	94±0.01
Poly-culture	22.63±0.10	271.18±7.96	248.55±8.04	1098.44±39.47	2.95±0.04	100±0.01

Table 3. Growth performance parameters of shrimp in monoculture and polyculture during the summer months for 120 days

Means with the same letter in the same row are not significantly different at $P<0.05$.

Shrimp	Growth performance					
	Initial weight (g)	Final weight (g)	Weight gain (g)	RBWG (%)	SGR (%/day)	Survival (%)
Mono-culture	1.6±0.01	21.0±0.83	19.4±0.83	1212.32±49.81	3.06±0.04	99±0.01
Poly-culture	1.6±0.01	20.75±0.62	19.15±0.62	1196.62±34.53	3.05±0.03	91±0.02

3- Feed utilization parameters

Tilapia in monoculture and polyculture

Table (4) shows that the feed utilization parameters did not significantly differ between the monoculture and polyculture systems. However, feed intake by tilapia was significantly higher in the monoculture system (319.59g/ kg feed) compared to the polyculture system (295.46g/ kg feed). This led to a slight, though not statistically significant, improvement in feed conversion ratio (FCR) in the polyculture system. The FCR values for tilapia were 1.24 in monoculture and 1.19 in polyculture, with no significant difference between the systems ($P> 0.05$).

Similarly, the feed efficiency ratio (FER) did not differ significantly, with values of 80.67 and 84.12% in the monoculture and polyculture systems, respectively. However, protein intake was significantly greater ($P< 0.05$) in the monoculture system (89.76) compared to the polyculture system (84.21). Despite this, the protein efficiency ratio (PER) values were not significantly different, ranging from 2.86 in monoculture to 3.02 in polyculture.

One explanation for these results may be that tilapia in polyculture systems consumed residual shrimp feed, reducing feed waste and potentially improving feed utilization and water quality. **Santos and Valenti (2002)** noted that competition for food is minimal when tilapia feed is readily available in polyculture systems. **Yuan *et al.* (2010**) similarly reported no statistically significant differences in FCR in tilapia–shrimp polycultures. Likewise, **Junior (2012)** observed no significant variations in FCR when evaluating tilapia and shrimp grown together in co-culture systems.

Polyculture with tilapia has also been shown to improve feed utilization, enhance water quality, and increase overall yield and profitability **(Wang & Lu, 2016)**. The co-culture of tilapia with the whiteleg shrimp has demonstrated advantages over shrimp monoculture, including better nutrient utilization, improved production efficiency, and reduced environmental impact **(Sun *et al.*, 2011; Hernández-Barraza *et al.*, 2013; Fitzsimmons & Shahkar, 2017; Lopez-Gomez *et al.*, 2017; Juarez-Rosales *et al.*, 2020)**.

Shrimp in monoculture and polyculture

Table (5) presents the feed utilization parameters of shrimp in both monoculture and polyculture systems over a 120-day period. The data showed no significant differences ($P> 0.05$) in feed intake, feed conversion ratio (FCR), feed efficiency ratio (FER), protein intake (PI), or protein efficiency ratio (PER) between the two systems. Although shrimp in monoculture consumed more feed than those in polyculture, the difference was not statistically significant.

The FCR values for shrimp ranged from 1.77 to 1.80 across both systems, again with no significant differences observed. Similarly, FER, PI, and PER values did not significantly vary between culture systems, though slightly higher values were recorded in polyculture (55.70 for FER, 9.36 for PI, and 2.00 for PER).

These results suggest that the presence of tilapia did not interfere with shrimp feeding behavior or efficiency. This may be due to the species occupying slightly different layers of the water column and the use of sinking feed, which allowed shrimp to feed undisturbed. Additionally, tilapia likely did not outcompete shrimp for feed due to differences in agility and spatial behavior.

Yi *et al.* (2004) reported that a shrimp stocking density of 30/m², combined with 0.25/m² of the Nile tilapia at salinities between 2 and 5ppt, resulted in improved shrimp production and better FCR compared to shrimp monoculture. Similarly, **Simão *et al.* (2013)** found that stocking density and feeding strategy in tilapia–shrimp polyculture systems did not significantly affect shrimp feeding performance. This was attributed to the higher mobility of tilapia, which allowed them to obtain feed efficiently without hindering shrimp access to food.

Table 4. Feed utilization parameters of tilapia in monoculture and polyculture during the summer months for 120 days

Means with the same letter in the same row are not significantly different at $P < 0.05$.

Tilapia	**Feed utilization**				
	Feed Intake (g feed/take)	**FCR**	**FER**	**PI**	PER
Mono-culture	319.59±0.99[a]	1.24±0.02	80.67±1.26	89.76±0.10[a]	2.86±0.12
Poly-culture	295.46±0.40[b]	1.19±0.03	84.12±2.84	84.21±1.65[b]	3.02±0.22

Table 5. Feed utilization parameters of tilapia in monoculture and polyculture during the summer months for 120 days

Means with the same letter in the same row are not significantly different at $P<0.05$.

Shrimp	**Feed utilization**				
	Feed Intake (g feed/take)	**FCR**	**FER**	**PI**	**PER**
Mono-culture	34.37± 0.10	1.77±0.08	56.45±2.54	9.72±0.27	1.92±0.14
Poly-culture	34.36± 0.44	1.80±0.03	55.70±1.10	9.36±0.15	2.00±0.04

4- Economic evaluation

The economic evaluation of tilapia and shrimp farming in monoculture and polyculture systems is summarized in Table (6). The results indicate that the cost range for monoculture ponds—whether tilapia or shrimp—was higher than that for polyculture systems. Notably, the production cost for tilapia monoculture was greater than that for shrimp monoculture.

However, when evaluating income from the total crop, polyculture systems—where both tilapia and shrimp were farmed together in the same pond—generated the highest total income. This was followed by income from tilapia monoculture, which exceeded that from shrimp monoculture.

These findings suggest that while tilapia monoculture incurs higher production costs, polyculture yields better overall economic returns. Although net income from tilapia monoculture was higher than that from shrimp monoculture, the return on cost was the greatest in the polyculture system, highlighting an improved economic efficiency and a better utilization of resources.

This is consistent with findings from the study of **Bejerano (2001)**, who reported that net income from shrimp can be maximized when co-cultured with tilapia. Similarly, **Alam *et al.* (2008)** demonstrated that tilapia–shrimp polyculture is both technically feasible and economically attractive when supported by an appropriate feeding strategy. **Junior (2012)** also noted that polyculture systems offer superior economic and performance indicators compared to monocultures.

With respect to undiscounted financial indicators, the tilapia–shrimp polyculture (TSP) model had the shortest investment payback period—2.82 production cycles—compared to shrimp monoculture (SM) and tilapia monoculture (TM). This faster recovery of initial investment makes the TSP model more appealing to investors than either monoculture system.

Furthermore, the TSP model demonstrated superior financial and economic performance, achieving a revenue-to-cost ratio of 1.57, indicating greater profitability. It also had the lowest operational ratio, reflecting more efficient resource use. The TSP system showed high returns on revenue (63.51%), cost (36.49%), and investment (82.88%), confirming its strong economic viability.

Critically, the internal rate of return (IRR) for the TSP model reached 117%, far exceeding the Egyptian Central Bank's discount rate of 27.75% **(Central Bank of Egypt (CBE), 2023)**. In contrast, the IRRs for the SM and TM models were considerably lower—9% and 3%, respectively—making them less financially viable in comparison.

Table 6. Economic evaluation of tilapia and shrimp in monoculture and polycultures during the summer months for 120 days

Economic evaluation	**Unit Price**	**SM**	**TSP**	**TM**

Costs	Feed Intake **(**kg**)**			11.405	44.639	34.426
	Feed cost **(**US$**)**		0.6	6.5	25.5	19.7
	Seeds used (1000)	Shrimp	6	250	250	
		Tilapia	3	-	100	100
	Fish Seeds cost **(**US$**)**			1.5	1.8	0.3
	Operation cost **(**US$**)**			10	10	10
	Consumption			16.22	33.60	26.99
	Total Costs **(**US$**)**			18.02	37.33	29.99
	Investment cost			34.24	70.93	56.98
Income	Pond Crop	Shrimp	6.29	5.18	4.732	-
		Tilapia	2	-	27.119	26.394
	Revenue **(**US$**)**			22.79	58.79	36.95
	Net Profit **(**US$**)**			4.77	21.45	6.96
	% Profit to cost			26.46	57.47	23.21
Undiscounted Criteria	Payback period			5.21	2.82	3.71
	Operation ratio			79.08	63.51	81.16
	Return on investment			66.56	82.88	64.85
	Revenue on cost			1.26	1.57	1.23
	Return on revenue			20.92	36.49	18.84
Discounted Criteria	IRR %			9	117	3

These results are consistent with financial theory and previous research, which emphasize the importance of key indicators—such as payback period, revenue-to-cost ratio, operating ratio, and internal rate of return (IRR)—in evaluating investment feasibility **(Damodaran, 2012; Brealey *et al.*, 2020)**. The strong economic returns achieved in this study align with the findings of **El-Naggar *et al.* (2008)**, who demonstrated the economic viability of integrated aquaculture systems involving tilapia and mullet.

In contrast to that study, which reported a decrease in the operating ratio, the present study observed an increase—suggesting improved efficiency in the use of economic resources. This further supports the superior performance of the TSP model.

Additionally, the current findings are in line with **Kasim *et al.* (2024)**, who reported strong economic performance using indicators such as net present value (NPV), return on investment (ROI), IRR (176.76%), benefit–cost ratio (BCR), and payback period (PP). While the IRR reported by **Kasim *et al.* (2024)** exceeds the TSP model's IRR of 117%, both values indicate high economic feasibility.

The superior performance of the TSP model across multiple financial indicators confirms its status as the optimal choice among the evaluated culture systems.

Technical and economic efficiency

Technical and economic efficiency for fry: All the models achieved full technical efficiency in both constant and variable yield cases. They also achieved full economic efficiency in the case of constant and variable yield on capacity, whereas the first model needed to increase the number and quality of the introduced seed to reach the optimal economic efficiency level, as it achieved 45% efficiency, i.e., it was inefficient **(**in the case of constant yield on capacity**)**. Therefore, changing the yield on capacity is the best choice to achieve optimal technical and economic efficiency from the fry input.

Technical and economic efficiency for feed: All the models achieved full technical efficiency in the cases of constant and variable yields, whereas the first and third models need to increase the quantity and quality of the feed input to reach the optimal economic efficiency level, as the efficiency of each of them decreases to 0.87 and 0.42%, respectively, meaning that the first is relatively efficient, whereas the third is inefficient. The second model achieved full economic efficiency in the case of constant yield on capacity. However, in the case of variable yield on capacity, the first and second models achieved full efficiency, whereas the efficiency of the third model decreased to 46%. Therefore, changing the yield on capacity is the best choice to achieve optimal technical and economic efficiency from the feed input in the first model. In contrast, the optimal efficiency is achieved in both cases in the first and third models, taking into account increasing the quantity of feed in the third model.

Chart (1), Economic Effiency of Study Models

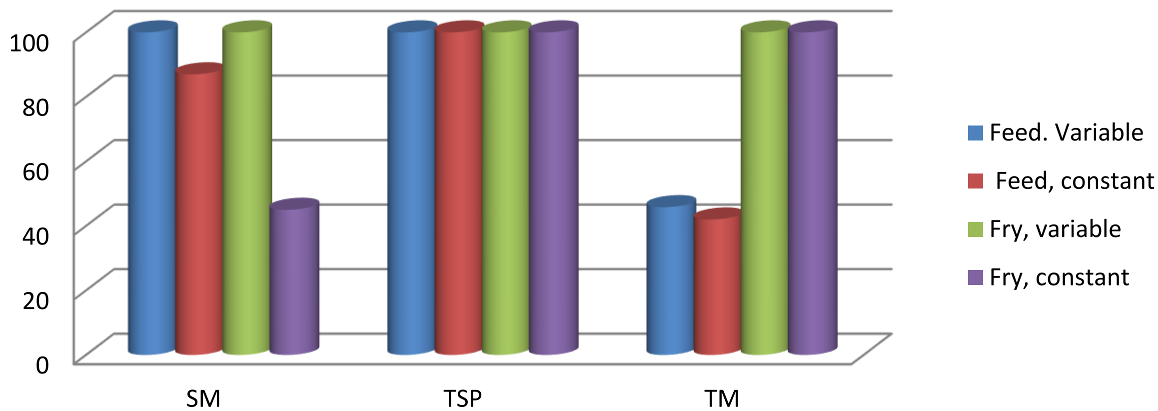
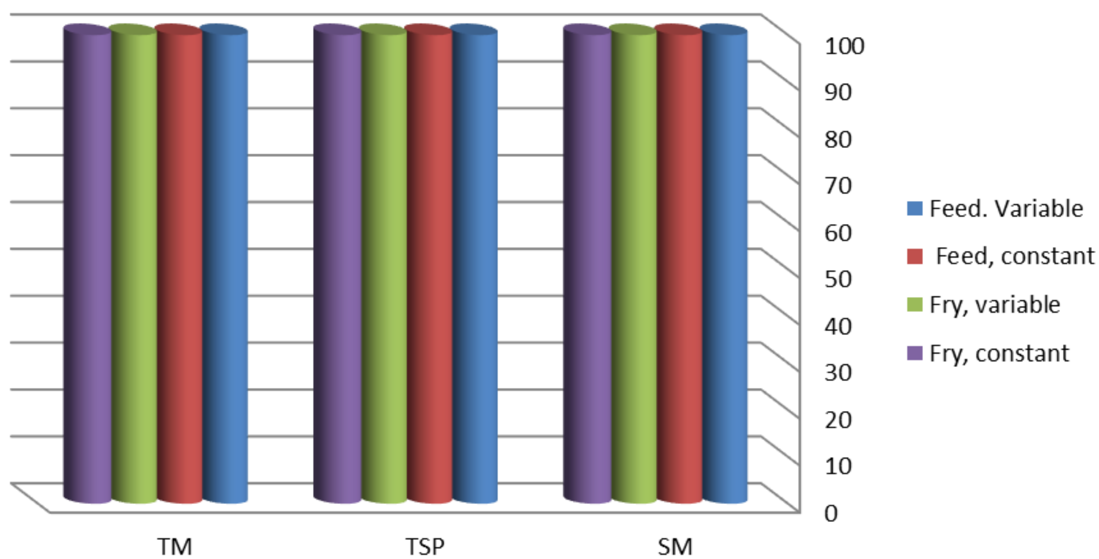


Chart (2), Technical Efficiency of Study Models



Wide variations in technical efficiency (TE) scores have been observed when farms are categorized by size, highlighting the importance of stocking density in achieving optimal space utilization, as demonstrated by the present research. Additionally, there is a growing need for species diversification to enhance both productivity and efficiency **(Misraa, 2014)**.

Economic and technical efficiencies have been assessed using Data Envelopment Analysis (DEA), which emphasizes that utilizing high-quality inputs without unnecessary waste can significantly improve efficiency levels **(Zhaoqun *et al.*, 2018; Mostafa *et al.*, 2019)**. Greater economic efficiency was achieved under variable returns to scale compared to constant returns, despite using the same amount of resources. This finding supports the conclusions of **Ahmed (2021)**.

The results also revealed that technical efficiency was achieved at a higher level than economic efficiency in the TM model (tilapia monoculture), under both variable and constant returns to scale, and in the SM model (shrimp monoculture), specifically in relation to feed and fry feed inputs under constant returns. These findings indicate that variable returns to scale lead to a higher level of efficiency in resource utilization.

However, the results also differed in terms of feed and fry input reduction. This variation may be attributed to differences in experimental conditions and the species cultivated. According to **Saleh (2022)**, both fry and feed inputs must be increased in SM and TM models to attain optimal economic efficiency.

In general, the technical and economic efficiency of fish farmers remains low. Only a small proportion of systems are both technically and economically efficient. However, when resources such as feed and fingerlings are used effectively, higher economic productivity can be achieved **(Aboua, 2023)**.

CONCLUSION

In conclusion, the water physicochemical parameters were within the ideal range for the cultivated species. This experiment suggests that culturing tilapia and shrimp in a polyculture system may be a viable option for improving growth performance, feed utilization, and survival. Furthermore, compared with monocultures, polycultures resulted in better economic and performance indicators. Notably, this trial is the first of its kind in Egypt. However, more research is needed to understand the mechanisms behind these findings and to identify best practices for tilapia and shrimp farming in polyculture systems to improve growth performance and survival.

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Competing interests

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

Data availability

The datasets generated or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

Ethical approval:

The authors followed all applicable guidelines **(**international, national, and/or institutional**)** for caring for and using fish under experimental conditions while designing the experiments. The animal studies adhered to the norms and criteria set out by ARRIVE **(**https://arriveguidelines.org/**)**. The Agricultural Research Center, Giza, Egypt, authorized all operations in accordance with the IACUC protocol number ARC CLAR 1625

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