Ann. Anim. Sci., Vol. 25, No. 3 (2025) 1155–1169 *DOI: 10.2478/aoas-2025-0019*

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IS INTEGRATED MULTI-TROPHIC AQUACULTURE-RICE CO-CULTURE AN UNREALISTIC OR FEASIBLE APPROACH TO PROVIDING ESSENTIAL CROPS, OPTIMIZING FEED CONVERSION RATIO, NITROGEN AND PHOSPHORUS USE EFFICIENCY?

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Abstract

Rice is not a horticultural crop, thus the idea that indoor cultivation cannot compete with outside production in desert and non-urban areas with shortages of water and challenging cultivation circumstances. The study intends to offer critical crops to poor communities through small-scale aquaponics systems that can adapt to climate change, despite some doubts about its feasibility. This study investigates the potential of integrated agriculture-aquaculture systems (IAAS) to enhance water, nitrogen, and phosphorus use efficiency (WUE, NUE, and PUE) while extending the nutrient cycle for rice and aquatic animal culture under climate adaptation conditions using greenhouses. This trial contained four treatments administered over 90 days. Two types of tilapia (T)-rice (R) co-culture systems and integrated multi-trophic-aquaculture (IMTA)-rice (R) co-culture systems were evaluated using two rice hydroponic culture techniques: floating raft system (FRS, T-R-FRS, and IMTA-R-FRS) and nutrient film technique (NFT, IMTA-R-NFT, and T-R-NFT). All treatments were carried out in two independent greenhouses equipped with indoor recycling closed systems and 10 kW solar panels. The FRS-R-IMTA system has superior rice properties compared to the NFT system. IMTA-R aquaponic and tilapia-R monoculture systems can reduce nutrients and water waste while increasing crop yields. These represent a potential solution to the challenges of climate change, which necessitates a more sustainable and resilient food production system. The IMTA system's apparent FCR values (0.73) surpass those of the tilapia monoculture system (1.58). IMTA-developed technology enables farmers to profitably culture a diverse species of aquatic animals without the need for costly extra feed. The results showed that coupled IMTA-R and T-R using the FRS technique are more promising for optimizing NUE and PUE efficiency than the NFT technique, as well as for producing a wider range of aquatic animals (such as mullets, crayfish, freshwater clams, and silver carp) than the T-R-FRS.

Key words: IMTA, greenhouses, Nile tilapia, floating raft system, nutrient film technique, nutrient and water use efficiency, FRS

Climate change poses major challenges to food production worldwide (Owusu and Asumadu-Sarkodie, 2016). Temperature and rainfall patterns are influencing crop yields, water availability, soil fertility, and global aquaculture production (Ahmed et al., 2019). A possible approach to cope with climate change is to integrate agriculture with aquaculture systems that may offer several benefits, including optimizing water, nitrogen, and phosphorus use efficiency (WUE, NUE, and PUE, respectively), which can help these sectors to adapt to climate change (Allison et al., 2007; Molden, 2013; Cradock-Henry et al., 2020). Furthermore, integrated systems may produce a more secure and resilient food production system that is better suited to changing climate conditions (Nenciu et al., 2022).

Rice is the primary food source for approximately 50% of the world's population (Ahmed and Garnett, 2011). Providing a reliable supply of rice is crucial for the future food security of the world's poor, many of whom reside in developing countries and rely on rice as a daily staple (Seck et al., 2012). However, supplying rising rice consumption without increasing environmental costs is a key problem for global rice farming (Halwart and Gupta, 2004). The global production of rice is growing about 1% annually and could increase even faster, with some analysts suggesting that total production must double by 2050 to keep pace with population growth (Kumar et al., 2023; Bin Rahman and Zhang, 2023). Rice can be used as a co-cultivation in aquaculture systems, creating beneficial habitats for numerous aquatic animals (Frei and Becker, 2005; Mohanty et al., 2004; Tarigan et al., 2021; Hu et al., 2016) or aquatic invertebrates (Li et al., 2021; Hu et al., 2016).

Integrated production systems include fish-livestock cultivation (Leng et al., 1995), fish-rice cultivation (Weimin, 2010), aquaponics (Palm et al., 2018), and integrated multi-trophic aquaculture (IMTA) (Ridler et al., 2007). This type of culture involves a more complex approach, combining a variety of plants and/or aquatic animals in a single system (Buck et al., 2018). Each of these systems has advantages and disadvantages, and the one chosen will be based on several of criteria, including available resources, desired level of production, and the type of aquatic animals or plants produced (Ask and Azanza, 2002; Bregnballe, 2022).

The most three common integrated production systems are hydroponics, aquaponics and IMTA (Bregnballe, 2022). Hydroponics is modern in many countries like Egypt, where it is used to produce lettuce and other plants to a limited extent (Bakr et al., 2023). Hydroponics system balances the accumulation of waste nutrients from fish culture water use while producing vegetables that may be sold, which is vital for aquaponics' financial sustainability (Rakocy, 2012). There are three hydroponic growing systems: gravel bed system (GBS), floating raft system (FRS), and nutrient film technique (NFT). FRS and NFT are more valuable commercially than GBS (Lennard and Leonard, 2006). A hydroponic growing system within an aquaponics framework may be chosen based on the distinct benefits that a certain hydroponic component provides (Rajalakshmi et al., 2022).

Aquaponics, which integrates aquaculture and horticultural production, has recently been recognized as a sustainable alternative (Ibáñez Otazua et al., 2022). Improving the physical and chemical properties of water may enhance nutrient management and efficiency in fish cultivation, especially for nitrogen (N) and phosphorus (P), providing a sustainable solution that can adapt to future climate change (Ahmed et al., 2022; Somerville et al., 2014).

IMTA is an aquaculture technology that cultivates several species in the same system, using waste from one species to provide nutrients to another (Chary et al., 2020). This integrated approach involves taking advantage of the aquatic environment's diverse trophic levels of food in order to enhance environmental sustainability (Fang et al., 2016). To achieve optimum outcomes in the IMTA system, careful selection of appropriate species and population sizes is required to support optimal biological and chemical processes, hence improving ecosystem health and encouraging industry sustainability (Khanjani et al., 2022).

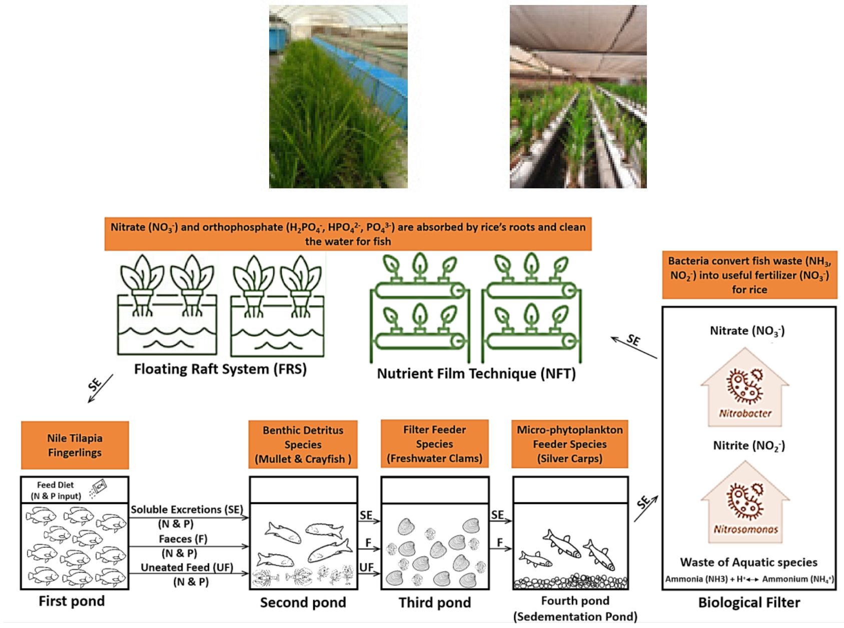
One of the most significant challenges facing aquaculture is how to effectively use WUE, NUE, and PUE fish waste by establishing unique and sustainable culture systems with the potential to reduce pollution resulting from aquaculture in accordance with climate adaptation guidelines (Folke and Kautsky, 1992). Integrated tilapia-rice-monoculture (T-R) systems have the potential to improve WUE, NUE, and PUE (Reddy and Kishori, 2018; Goda et al., 2023). These approaches have been shown to reduce nutrient and water losses, increase crop yields, and improve soil health. Furthermore, by selling both rice and fish, they may increase farmers' income. This approach offers optimum use of water and nutrients because the tilapia feed on rice straw and their excrement fertilizes the rice (Reddy and Kishori, 2018). Therefore, the current study's concept aims to develop and evaluate the feasibility of combining four aquaculture (monoculture and IMTA) and aquaponic (FRS and NFT) systems, all in a greenhouse environment and in all cases, rice is the sole major plant grown, as a novel concept of integrated agriculture-aquaculture systems (IAAS), in order to optimize the WUE, NUE, and PUE, as well as increase the cycle of nutrients produced by raising IMTA using hydroponically grown rice.

Figure 1. Schematic diagrams of the current experimental designs of treatments 2 to 5; (a) Greenhouse 1 and (b) Greenhouse 2

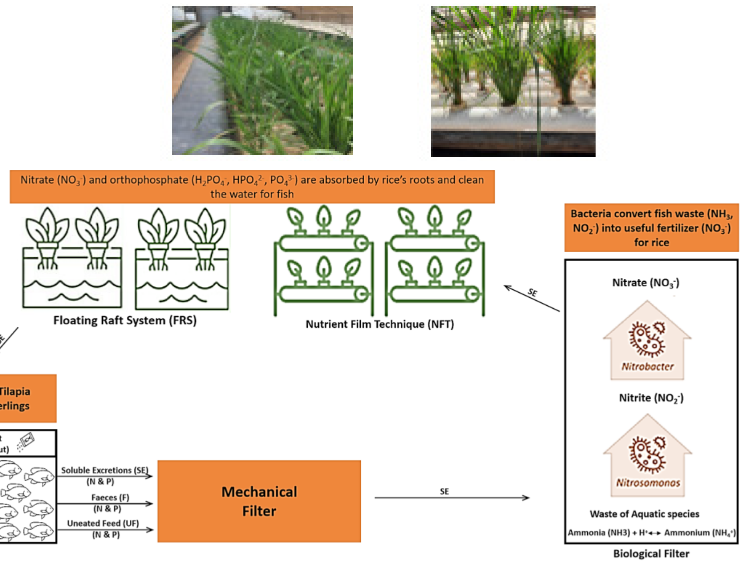
Material and methods

Experimental techniques

In the current study, for a period of 90 days, two types of integrated aquaculture-rice systems: Tilapia (T)-rice (R) system (T-R), and integrated multi-trophic-aquaculture **(**IMTA)-rice (R) system (IMTA-R) were evaluated within two rice-culture techniques: floating raft system (FRS) and nutrient film technique (NFT). Four treatments were conducted in this study. Treatments 1 and 2 were IMTA-R polyculture systems using FRS (IMTA-R-FRS) and NFT (IMTA-R-NFT) techniques, respectively. Treatments 3 and 4 were T-R monoculture systems using FRS (T-R-FRS) and NFT (T-R-NFT) techniques, respectively. All treatments (IMTA-R-FRS, IMTA-R-NFT, T-R-FRS, and T-R-NFT) were carried out in two independent greenhouses equipped with in-door recycling closed systems (Figure 1 a and b). The indoor-recycling closed system is powered by combining grid power and solar energy. The solar panels with a total capacity of 10 KW provide enough energy to operate the water pumps and the air blowers from 8:00 to 15:00 h. A closed aeration network distributes air through air nozzles and nano-hose discs to the different units of the system. The aeration network relies on two air blowers (Siemens and Schmalz) that operate alternatively with an interval of 30 minutes employing automatic timers 24 h day^{-1}.



(IMTA-R-FRS and IMTA-R-NF techniques, a)



(T-R-FRS and T-R-NFT techniques, b)

Figure 2. The aquatic species cultivated in the experiment

Experimental systems

The fish representing the IMTA system (Figure 2) were maintained in four cement ponds (40 m^3 each). In the first cement pond, fingerlings of Nile tilapia, *Oreochromis niloticus* (L.), were placed. In the second cement pond, a polyculture of benthic aquatic detritus species (mullet, *Liza ramada*, crayfish, *Procambarus clarkia*) was stocked. The third cement pond was filled with filter feeder freshwater clams, *Aspatharia chaiziana* and *Aspatharia* spp. both from the Iridinidae family. Finally, silver carp, *Hypophthalmichthys molitrix*, was introduced into the fourth cement pond, which is classified as a sedimentation pond to prevent phytoplankton multiplication. Water from the sedimentation pond is pumped to a large biological filter (6 m^3), where ammonia is converted to nitrite and then to nitrate. After nitrification, the water flows through a sand filter before being pumped to greenhouse-1, which including the IMTA-R-FRS and IMTA-R-NFT (Figure 1 a). Similarly, water flows from the tilapia pond to the sedimentation pond, biological filter, sand filter, and then to greenhouse-2, containing the T-R-FRS and T-R-NFT systems (Figure 1 b). Rice absorbs nitrogen in the form of NH_4, whereas other plants absorb nitrate (NO_3), therefore it may not require a biofiltration system. The employment of a biological filter in the experiment is linked to the system architecture. We could not remove it from the design because it was previously used in vegetable production, and we did not want to decrease the efficiency of the current setup method. The FRS and NFT units have mass flow rates of approximately 2.7 m^3 h^{-1} and 1.3 m^3 h^{-1}, respectively. The water ends in a 3 m^3 sump pond used for sedimentation (1.5 m^3 serving as a biological filter), whose goal is to reduce any amount of organic matter through sedimentation and to reduce, if any, the remaining ammonia group. Finally, the water flows to the first cement pond with Nile tilapia in the IMTA system. Regarding the NFT, the pipes were drilled to create holes 4 to 5 cm in diameter to match the size of the net pots. Plastic drinking pots were used as planting containers, with the bottom perforated (30 mm) to allow water to come into direct contact with the plant's roots. Simultaneously, in the FRS-TP system, a cement pond (a total of 22.5 m^3 water culture) was used. Each seedling was placed in plastic drinking pots and then inserted inside the holes in NFT and the floating styrofoam plate in FRS. To protect each seedling, 3 cm square pieces of synthetic sponge to fix and protect it inside the pots were used. The system's stability and operational parameters were maintained through the system operator and employee who provide general supervision of the systems, and supply all necessary tools, materials, and parts for proper system operation and maintenance. In addition the system is supported with a special electronic device that sets off an alarm when its sensor detects a problem with water and aeration.

Water quality analysis

For all the four treatments (IMTA-R-FRS, IMTA-R-NFT, T-R-FRS, and T-R-NFT), the water source was supplied from well water at El-Kanater El-Khayria fish station, Kalubiya Governorate, Egypt. The well water quality indices, total ammonia nitrogen (0.28±0.17 mg L^{-1}), total nitrate (0.22±0.15 mg L^{-1}), total nitrite (0.08±0.02 mg L^{-1}), and total phosphorus (0.21±0.09 mg L^{-1}), were determined weekly, according to standard methods described by APHA (1998). Temperature, DO, Ph, TP, TN and TAN were monitored twice a day (at 08:00 and 16:00) before feeding events, and floc volume (FV) was monitored once a day prior to the 8:00 h feeding. During the experiment, for all treatments, water quality parameters of temperature (°C), dissolved oxygen (mg L^{-1}), and pH were determined daily using an IoT system (WiFish from ReNile, Cairo, Egypt), consisting of 11 sensing nodes. These three parameters were recorded every 30 seconds and periodically transmitted to the data capture system.

Aquatic animals data and calculations

IMTA aquatic animals are based on the framework of an ecosystem strategy, which allows for complementing ecological functions by feeding only one species. In the current IMTA, once the tilapia is fed, much of the feed is either consumed for the fish's growth and metabolism or excreted as soluble and solid feces. Within the IMTA system (Figures 1 a), uneaten feed, feces, and soluble excretions are recaptured by subsequent extractive aquatic species (mullet, crayfish, freshwater clams, and silver carp), which use them as nourishment, taking advantage of synergistic interactions between the species that act as living filters. In either the IMTA or the monoculture system, the commercial meal (25% protein) was fed to the Nile tilapia twice a day, at 3% of fish biomass, and adjusted biweekly according to the increasing fish biomass. Before the experiment started, each aquatic species' initial body weight (IBW, g) was calculated. The first IMTA pond was supplied with 450 Nile tilapia fingerlings (136.43±1.43 g). The second pond was stocked with 165 crayfish (25.17±0.89 g) and 500 fingerling mullet (102.5±1.05 g). The third pond was placed with 176 freshwater clams (305.11±4.66 g). To prevent algae growth, 325 silver carp (144.09±1.45 g) were added into the fourth aquatic IMTA pond. Fish weight was determined every two weeks to calculate all metrics related to growth, feed utilization efficiency and nutrients retention throughout the study period. After 90 days, all aquatic animals were measured to determine their final body weight (FBW, g animal^{-1}), weight gain (WG, g animal^{-1}), feed conversion ratio (FCR), and specific growth rate (SGR, % days^{-1}). Feed intake (FI, g tilapia^{-1}), nitrogen intake (mg g^{-1} diet), and phosphorus intake (mg g^{-1} diet) were determined directly for Nile tilapia (the only species that feeds in the IMTA system) and estimated indirectly for the rest of the IMTA species using the following equations:

Weight gain (WG, g fish^{-1}) = FBW – IBW (1)

Feed conversion ratio (FCR, feed: gain) = Feed intake (g) / weight gain (g) (2)

The following formulae were used to obtain the cumulative feed conversion ratio value for each additional aquatic species introduced into the IMTA-system:

A cumulative FCR for mullets (feed: gain) = (3)

$$\frac{\text{Feed intake (g)}}{\text{weight gain of tilapia (g) + weight gain of mullets (g)}}$$

A cumulative FCR for other aquatic animals (feed: gain) = Feed intake (g) / (weight gain of tilapia (g) + weight gain of polyculture of mullets (g) + crayfish (g) + weight gain of mussels, and weight gain of silver carp (4)

Specific growth rate (SGR, % days^{-1}) = (5)

$$\left(\frac{\ln FBW - \ln IBW}{t}\right)$$

where: *FBW* is final body weight (g); *IBW* is initial body weight (g); *ln* = natural logarithmic; *t* = time in days.

Nitrogen (N) and phosphorus (P) calculation parameters

The calculated data values from this investigation were used to complete the N and P mass balance in the aqueous phase. Because well water offers insufficient nutrients (Yang and Kim, 2020 a), the nutrient intake from well water was neglected in this study. As a result, fish feed provided the sole source of nutrients in the current experimental system. To compute the mass of aqueous N and P in the NFT and FRS systems, weekly measurements of aqueous N group (TAN, NO_2, and NO_3) and P (PO_4) entering the NFT and FRS unit were taken. Fish N and P content was calculated using actual total N and P values measured from the entire fish. The mass of N and P species retained in the aquatic units and NFT and FRS systems, as well as the total N and P in the aqueous phases of both systems, were determined at the end of the experiment.

The mass balance was used to determine the N and P balances for fish-culture ponds and other experimental NFT and FRS systems using the following basic equations as described by Morales et al. (2018) and Yang and Kim (2020 b).

Nutrient intake (g) = total feed intake (g dry weight) × nutrient feed content (%) (6)

Total nutrient fish gain (g) = (final body weight (g) × final body fish nutrient content (%)) – (initial body weight (g) × initial body fish nutrient content (%)) (7)

Total nutrient pond gain (g) = total fish body nutrient gain (g) × total biomass pond production (g wet weight) (8)

Nutrient discharge (g) = nutrient intake (g) – nutrient fish gain (g wet weight) (9)

For mullets, crayfish, clams, and silver carp the following equations were used to predict (estimated) N and P balance values:

Nutrient (N or P) gain biomass (g) (mullets, crayfish, clams, and silver carp) = (final body weight (g) × final body nutrient content (%)) – (initial body weight (g) × initial body nutrient content (%)) (10)

Nutrient discharge (g) (clams, crayfish) = (nutrient discharge from Nile tilapia pond (g)) – nutrient (N or P) gain biomass for mullets and prawn pond (g) (11)

Nutrient discharge from clams (g) = nutrient discharge from mullets, crayfish pond (g) – nutrient (N or P) gain biomass for clams (g) (12)

Nutrient discharge from silver carp (g) = nutrient discharge from clams' pond (g) – nutrient (N or P) gain biomass for silver carp (g) (13)

Nutrient retention of nitrogen (N-retention) and phosphorus (P-retention) of all cultured aquatic animals was calculated according to Storebakken et al. (2000), based on the following formula:

$$\text{Nutrient retention} = 100 \times [(FBW \times C_f) - (IBW \times C_i)] / (\text{feed intake} \times C_{diet}) \quad (14)$$

where: C is the concentration of the nutrient (N or P), while i and f are the initial and final sampling days.

Rice culture, measurement, and calculations

No pesticides or antibiotics were applied at any stage in the rice hydroponic biofilter. Styrofoam tray methods were used for seedlings rice germination outdoors for 40 days and followed by seedlings in plastic pots after they achieved 4–7 leaves on the main stem, a plant height of 15–20 cm, and 1–3 tillers according to Dongmei et al. (2014). All experimental treatments (IMTA-R-FRS, IMTA-R-NFT, T-R-FRS, and T-R-NFT) used seed from the high-yielding rice variety, Sakha 101, obtained from the Agricultural Research Center, Ministry of Agriculture, Egypt. During the experiment, greenhouse conditions were maintained at TC 28.34–29.78, humidity 60–78%, and light intensity 1500–3000 lux from 8:00 to 17:00 h using artificial fluorescent lamps. Rice was harvested and measured for grain characteristics and yield after 90 days from transplanting (Figure 3). At the end of the experiment, the mean value of 15 randomly selected healthy planting pots (in triplicate) was calculated individually for leaves, stalks, and ears. The number of branches in a panicle, panicle length (cm) was measured as a linear distance from the neck-node of the panicle to the tip of the panicle, number of effective panicles, grain number per panicle, the number of grains was counted from 10 panicles collected and the collected data was averaged; thousand-grain weight (g), this was performed by randomly selecting 1,000 ripe kernels (g) and recording their weights; and yield (kg ha^{-1}) was measured according to Rasheed et al. (2021). Rice parts including stem, leaf, root biomass (kg m^{-2}), and rice kernel biomass (kg m^{-2}) were measured. Spikelet fertility (%) and seed setting rate (%) were calculated according to Prasad et al. (2006) using the following equation:

$$\textit{Spikelet fertility (\%)} = 100 \times \frac{\textit{(Filled Seed + Half-Filled Seed)}}{\textit{(Filled Seed + Half –Filled Seed + Unfilled Seed}} \quad (15)$$

$$\textit{Seed setting rate (\%)} = 100 \times \frac{\textit{Filled Seed}}{\textit{(Filled Seed + Half – Filled Seed + Unfilled Seed}} \quad (16)$$

Figure 3. The rice cultivation system

The total nitrogen and phosphorus contents (g m^2) of rice parts (stem, leaf, root, and kernel) were determined using standard procedures outlined by APHA (1998). Furthermore, the nitrogen and phosphorus retention (g m^2) of rice parts (stem, leaf, root, and kernel) were calculated according to Dong et al. (2012).

Statistical analysis

The hypotheses of homoscedasticity and normality were checked before the statistical analysis of data. Data were presented as mean ± SD (n = 5). All data were analyzed using the SPSS computer software package program by two-way ANOVA (analysis of variance) test. A repeated measures ANOVA test was used to examine significant differences between means at P≤0.05, followed by Duncan's multiple range test. Finally, GraphPad Prism (version 9) was utilized to create graphical representations of the aquatic animal data.

Results

Physicochemical parameters of water

In the current study, the water quality parameters of temperature, DO, Ph, TP, TN and TAN for both systems were still within the permissible limit. There were no significant (P≥0.05) differences in temperature (°C) levels between all treatments (Table 1). DO levels did not differ significantly (P≥0.05) between treatments with IMTA-R-NFT, T-R-FRS, and T-R-NFT. The treatment IMTA-R-FRS had the lowest significant (P≤0.05) value of DO. IMTA-R-NFT showed the highest pH value (P≤0.05), followed by IMTA-R-FRS, T-R-FRS, and T-R-NFT, respectively. IMTA-R-FRS and IMTA-R-NFT had the lowest (P≤0.05) values in TP and TN. A similar pattern was observed for total ammonia nitrogen (TAN), with either IMTA-R-FRS or IMTA-R-NFT, while both T-R-FRS and T-R-NFT exhibited high levels.

Rice growth and production indicators

The general characterization of rice production is shown in Figures 4–7. Overall, IMTA-R-FRS achieved the high values (P≤0.05) of panicle length (cm), the number of branches in a panicle, effective panicles (no.), and thousand-grain weight (g) (Figure 4). The high significant (P≤0.05) plant length was observed at IMTA-R-FRS treatment. Seed setting rate (%) and spikelet fertility rate (%) recorded the highest significant (P≤0.05) values for T-R-FRS and IMTA-R-FRS, respectively (Figure 5). While IMTA-R-NFT and IMTA-R-FRS recorded the highest values of grain number/panicle. No significant (P≥0.05) differences were recorded between all treatments in rice parts biomass (stem and kernel), while the IMTA-R-FRS treatments showed (P≤0.05) higher values of root biomass (Figure 6). Regarding total yield, between all treatments, the IMTA-R-FRS treatment achieved the high (P≤0.05) yield values (Table 2), while T-R-NFT recorded the lowest (P≤0.05) values.

Table 1. Averages of water physicochemical parameters of the experimental systems

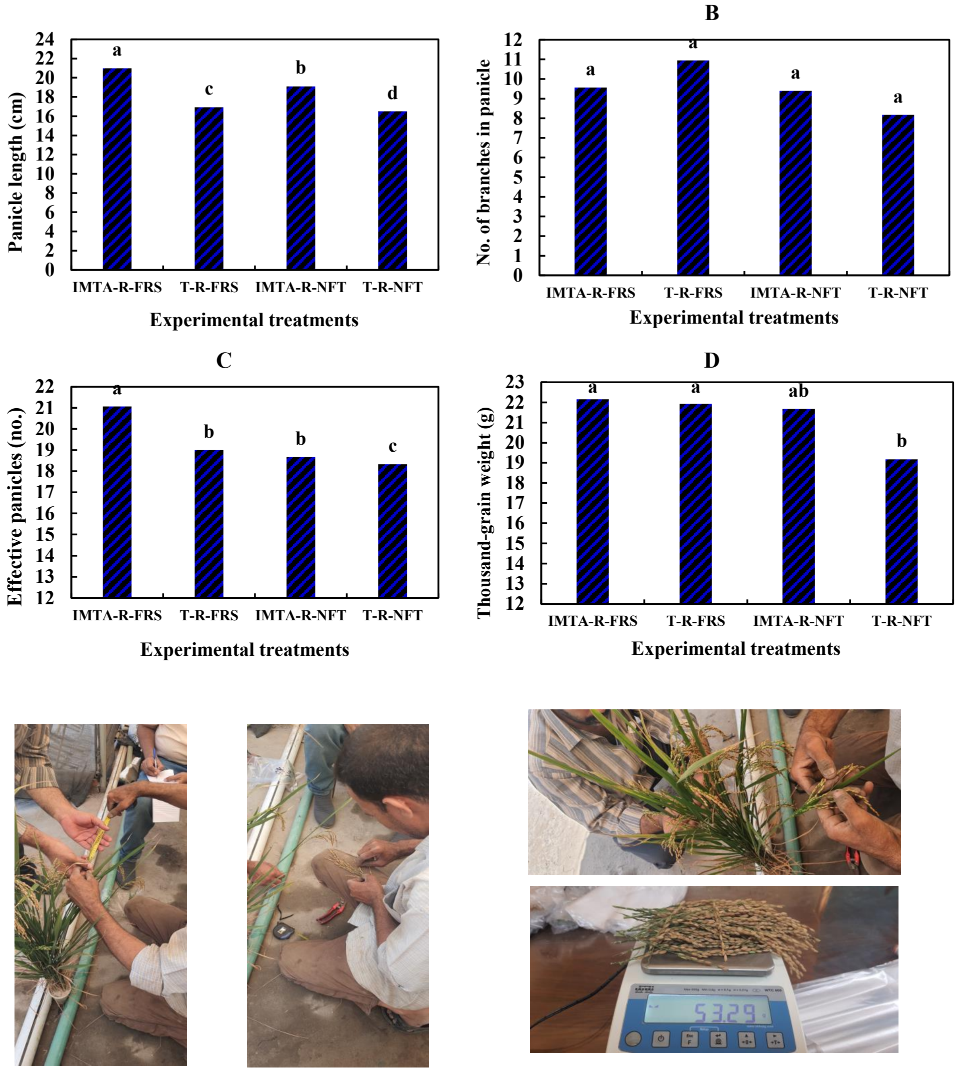
Water physicochemical parameters	Cultivation systems*			
	IMTA-R-FRS	T-R-FRS	IMTA-R-NFT	T-R-NFT
Temperature (°C)	27.26±1.37	28.23±1.13	28.14±1.95	28.23±1.13
DO (mg L^{-1})	4.51±0.14 b	6.18±0.47 a	5.78±0.16 a	6.11±0.47 a
pH	7.13±0.22 b	6.78±0.23 c	8.12±0.21 a	6.75±0.23 c
TP (mg L^{-1})	0.21±0.05 b	0.46±0.12 a	0.39±0.10 b	0.45±0.12 a
TN (mg L^{-1})	14.28±1.12 c	50.13±1.65 a	38.74±1.78 b	50.11±1.65 a
TAN (mg L^{-1})	0.32±0.16 b	0.64±0.10 a	0.26±0.21 b	0.64±0.10 a

*IMTA: integrated multi-trophic aquaculture, FRS: floating raft system, NFT: nutrient film technique, R: rice cultivation system, T: tilapia monoculture system. DO: dissolved oxygen (mg L^{-1}), TN: total phosphorus (mg L^{-1}), TN: total nitrogen (mg L^{-1}), and TAN: total ammonia nitrogen (mg L^{-1}). The presented data are mean ± SD (*n = 3*). The lowercase letters in the same row are significantly (P<0.05) different (a > b > c). The absence of lowercase letters means none are significantly (P<0.05) different between groups.

Table 2. Effect of different rice cultivation methods on rice total yield

Rice production characteristics	Cultivation systems*			
	IMTA-R-FRS	T-R-FRS	IMTA-R-NFT	T-R-NFT
Yield (g m^2)	880.18±89.25 a	583.75±20.69 b	487.03±2.25 b	252.75±1.1 c
Yield (kg ha^{-1})	8801.8±79.31 a	5837.5±26.96 b	4870.3±12.58 b	2527.5±12.5 d
Yield (kg Fadden^{-1})	3696.75±57.9 a	2451.74±24.9 b	2045.52±28.0 c	1061.56±28.0 d

*IMTA: integrated multi-trophic aquaculture, FRS: floating raft system, NFT: nutrient film technique, R: rice cultivation system, T: tilapia monoculture system. The presented data are mean ± SD (*n = 3*). The lowercase letters in the same row are significantly (P<0.05) different (a > b > c). The absence of lowercase letters means none are significantly (P<0.05) different between groups.



IMTA: Integrated Multi-Trophic Aquaculture, FRS: Floating Raft System, NFT: Nutrient Film Technique, R: Rice cultivation system; T: Tilapia monoculture system.

Figure 4. Effect of rice production systems on rice production characteristics of (A) panicle length, (B), number of branches in panicile, (C) number of effective panicles, and (D) thousand-grain weight (g)

Rice nutrient (N and P) contents

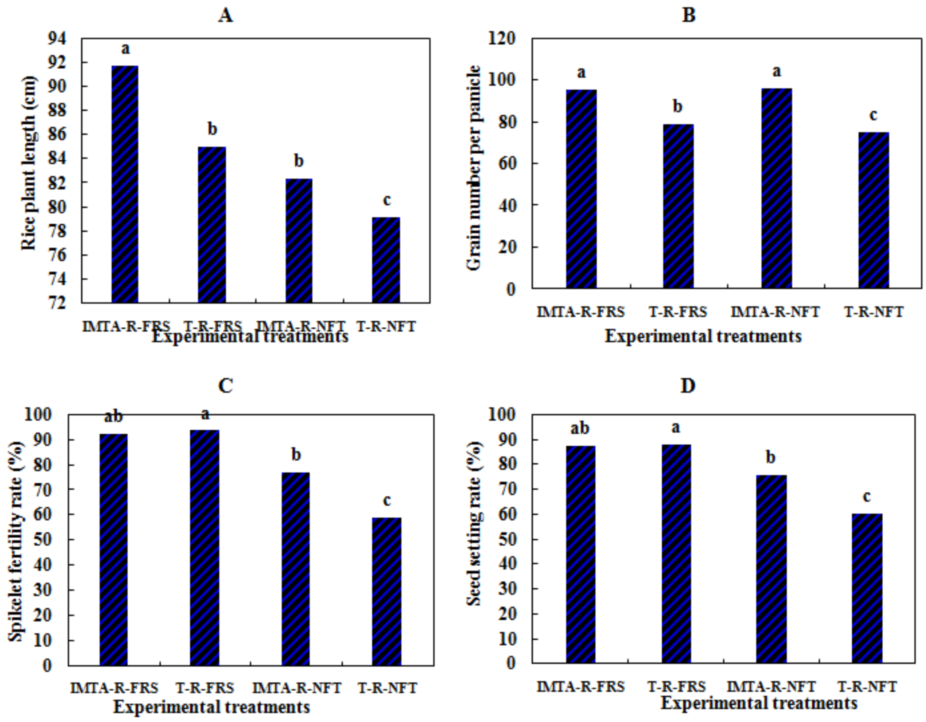
N- and P-content in the rice stem and leaf were identical (0.1 and 0.01 g m^2, Table 3). Treatment IMTA-R-FRS achieved the high significant (P<0.05) value in N-content in both rice root and kernel. Compared to NFT treatments, a higher value (P≤0.05) in P-content in rice root, kernel, and total rice was reported in FRS treatments (Table 3).

Rice nutrient (N and P) retentions

For all experimental treatments, no (P≥0.05) differences in N- and P-retention in rice stem, leaf, and root were found (Figure 7), except the T-R-FRS treatment (9.57% and 5.35%), which achieved highly significant (*P*≤0.05) values in P-retention of rice stem, leaf, and root. In all treatments, FRS (IMTA-R-FRS and T-R-FRS) treatments achieved highly significant (P≤0.05) values of N- and P-retention in rice kernel, compared to NFT treatments (IMTA-R-NFT and T-R-NFT).

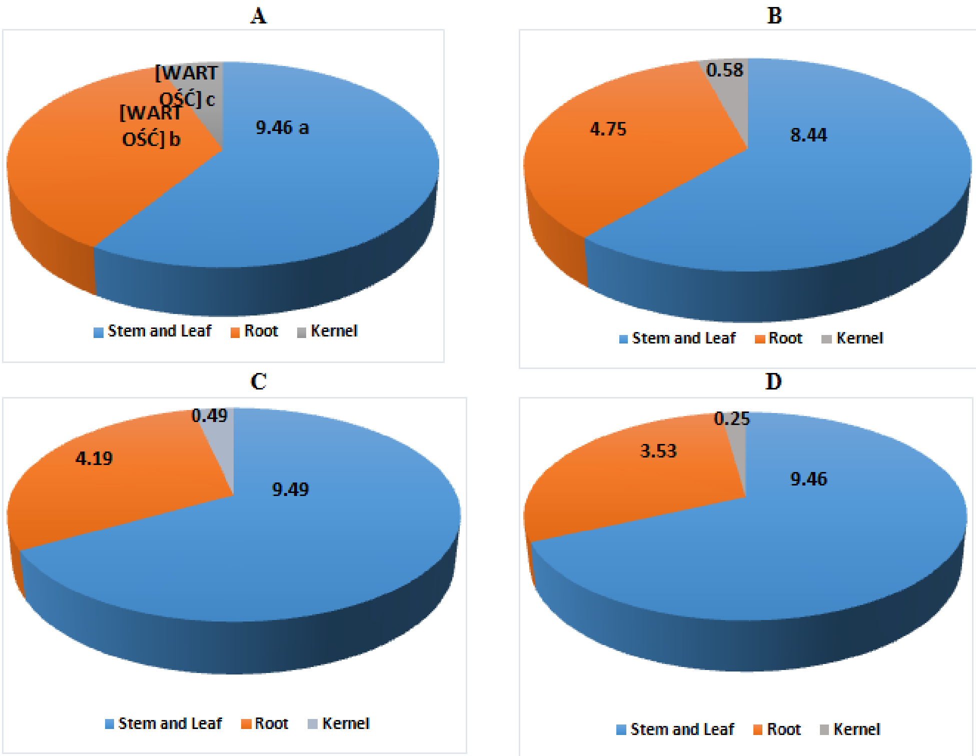
Aquatic animals growth indicators

Tilapia (as a monoculture system) had a feed intake of 625 g fish^{-1}, with N and P intakes of 1.3 and 2.0 g fish^{-1}, respectively. The FBW of tilapia (533 g fish^{-1}), mullet (146 g fish^{-1}), crayfish (31 g animal^{-1}), freshwater clams (361 g clam^{-1}) and silver carp (500 g fish^{-1}) was observed, while the IBW of tilapia (144.09 g fish^{-1}), mullet (136.43 g fish^{-1}), crayfish (102.50 g animal^{-1}), freshwater clams (25.17 g clam^{-1}) and silver carp (305.11 g fish^{-1}) (Table 4). Tilapia had the highest WG and SGR (396 g fish^{-1} and 2.2 % days^{-1}, respectively), followed by silver carp (356 g animal^{-1} and 2.1% days^{-1}, respectively), freshwater clams (56 g animal^{-1} and 1.1% days^{-1}, respectively), mullet (43 g fish^{-1} and 1.1% days^{-1}, respectively), and crayfish (6 g fish^{-1} and 0.8% days^{-1}, respectively).



IMTA: Integrated Multi-Trophic Aquaculture, FRS: Floating Raft System, NFT: Nutrient Film Technique, R: Rice cultivation system, T: Tilapia monoculture system.

Figure 5. Effect of different experimental treatments on rice production characteristics of (A) rice plant length, (B), grain number per panicle, (C) spikelet fertility rate, and (D) and seed setting rate



IMTA: Integrated Multi-Trophic Aquaculture, FRS: Floating Raft System, NFT: Nutrient Film Technique, R: Rice cultivation system, T: Tilapia monoculture system.

Figure 6. Effect of different rice production systems of (A) IMTA-R-FRS, (B) IMTA-R-NFT, (C) T-R-FRS, and (4) T-R-NFT systems on rice parts biomass (kg m2)

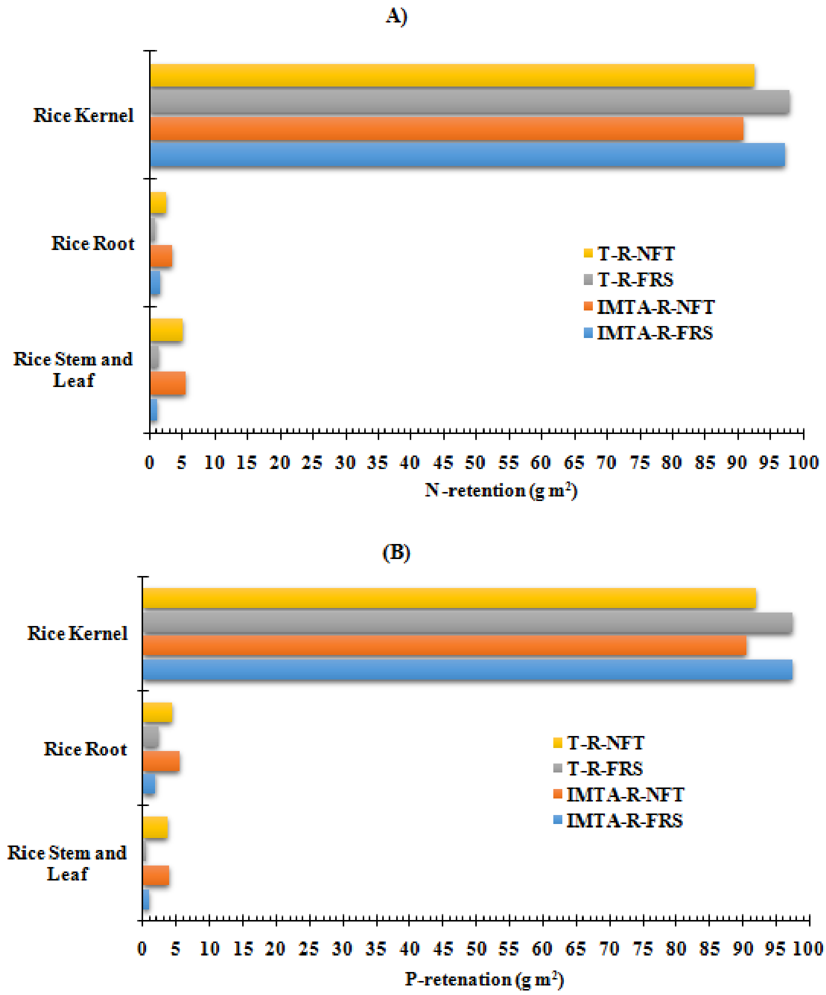


Figure 7. Effect of experimental treatments on nitrogen (A) and phosphorus (B) Retention (%) of rice parts. IMTA: Integrated Multi-Trophic Aquaculture, FRS: Floating Raft System, NFT: Nutrient Film Technique, Rice cultivation system, T: Tilapia monoculture system

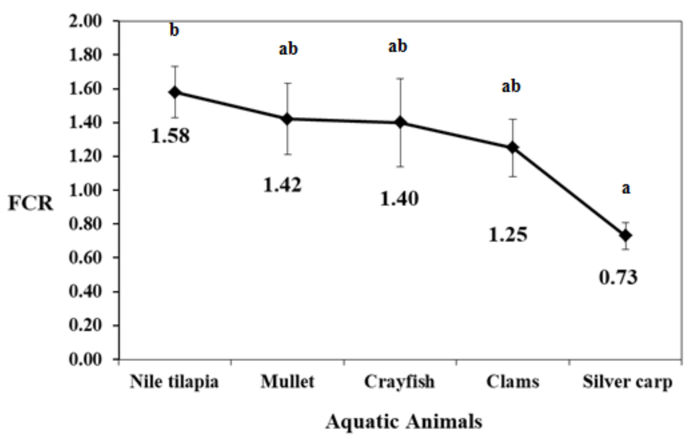


Figure 8. Cumulative FCR obtained by adding different aquatic animal species to the IMTA system

Cumulative FCR

There is an improvement of cumulative FCR values observed each time a new aquatic species is introduced into the IMTA-system compared to tilapia if considered as a monoculture system (Table 4). The apparent cumulative FCR values for the IMTA system were 0.7, compared to 1.6 for the tilapia culture only. Thus introducing new species into IMTA-system proved the concept of improving cumulative FCR with successive species introduction into the system (Figure 8). Given that tilapia were the only species fed in the IMTA system (625 g fish^{-1}), and that the remaining aquatic species used the waste of previous aquatic species as a food source.

Table 3. Effect of rice cultivation methods on nitrogen and phosphorus contents of rice parts

Nitrogen and phosphorus contents based on rice parts	Rice cultivation systems*			
	IMTA-R-FRS	T-R-FRS	IMTA-R-NFT	T-R-NFT
N-content (g m^2)				
Rice stem and leaf	0.10 ±0.01	0.10±0.03	0.11±0.02	0.10±0.04
Rice root	0.15±0.03 a	0.06±0.01 b	0.07±0.00 b	0.05±0.00 b
Rice kernel	8.75±0.67 a	7.00±1.05 b	1.75±0.22 c	0.07±0.01 d
Total	9.00±1.18 a	7.16±0.32 b	1.93±0.43 c	0.22±0.00 d
P-content (g m^2)				
Rice stem and leaf	0.01±0.01	0.01±0.00	0.01±0.00	0.02±0.00
Rice root	0.03±0.01 a	0.02±0.01 a	0.02±0.00 a	0.01±0.00 b
Rice kernel	1.25±0.12 a	1.00±0.16 a	0.25±0.01 b	0.01±0.00 c
Total	1.29±0.21 a	1.03±0.28 a	0.28±0.05 b	0.04±0.01 c

*IMTA: integrated multi-trophic aquaculture, FRS: floating raft system, NFT: nutrient film technique, R: rice cultivation system, T: tilapia monoculture system. N- and P-contents: Nitrogen and phosphorus contents (g m^2). The presented data are mean ± SD ($n = 3$). The lowercase letters in the same row are significantly ($P<0.05$) different (a > b > c). The absence of lowercase letters means none are significantly ($P<0.05$) different between groups.

Table 4. Growth performance, N-intake (mg/g), and P-intake (mg/g) of different aquatic animal culture in IMTA systems

	Nile tilapia	Mullet	Crayfish	Freshwater mussels	Silver carp
IBW (g/fish)	136.43±1.43	102.50±1.05	25.17±0.89	305.11±4.66	144.09±1.45
FBW (g/fish)	532.50±3.16	145.76±1.45	31.11±1.21	360.93±4.89	500.15±3.65
WG (g/fish)	396.07±3.11	43.26±1.48	5.94±1.23	55.82±4.10	356.06±3.43
Cumulative WG (g)	–	439.33*	445.27*	501.09*	857.15*
SGR (%/days)	2.18±0.53	1.12±0.08	0.75±0.11	1.12±0.28	2.07±0.34
FI (g/fish)	625.45	–	–	–	–
FCR	1.58±0.38	–	–	–	–
Cumulative FCR	–	1.42*	1.40*	1.25*	0.73*
N intake (mg/fish)	1,250.90	–	–	–	–
P intake (mg/fish)	1,980.80	–	–	–	–
Survival (%)	98.0	98.0	90.90	85.23	92.31
Total biomass (kg)**	260.93	71.42	4.67	54.14	150.04

* Estimated
** The total biomass (kg 40 m^3) was calculated over 90 days.

Table 5. Nitrogen and phosphorus retention of both aquatic animals and rice cultivated under different IMTA and mono-culture systems

	Nutrients management			
	N-intake (mg animal^{-1})	N-retention (%)	P-intake (mg animal^{-1})	P-retention (%)
1	2	3	4	5
Intake (mg tilapia fish^{-1})	1250.89	–	1,980.80	–
IMTA aquatic animals				
Tilapia	851.44	68.07	368.54	18.61
Mullets	32.24	2.58	117.21	5.92
Crayfish	2.45	0.2	2.52	0.13
Clams	11.54	0.92	29.01	1.46
Silver carp	178.89	14.3	574.46	29
Total	1076.56	86.07	1091.74	55.12
Rice culture				
R-FRS (mg m^2)	119.69	9.57	105.99	5.35
R-NFT (mg m^2)	15.61	1.25	13.99	0.71
Total IMTA-R-FRS	1196.25	95.64	1197.73	60.47
Total IMTA-R-NFT	1092.17	87.32	1105.73	55.83

Table 5. Nitrogen and phosphorus retention of both aquatic animals and rice cultivated under different IMTA and mono-culture systems

1	2	3	4	5
Tilapia monoculture systems				
Tilapia	851.44±4.56	68.07	368.54±3.34	18.61
Rice grain				
FRS (mg m^2)	28.14±2.79	2.25	24.84±1.68	1.25
NFT (mg m^2)	2.65±0.09	0.21	2.64±0.07	0.13
Total T-R-FRS	879.58	70.32	393.38	19.86
Total T-R-NFT	854.09	68.28	371.18	18.74

*IMTA: integrated multi-trophic aquaculture, FRS: floating raft system, NFT: nutrient film technique, R: rice cultivation system, T: tilapia monoculture system. The presented data are mean ± SD (*n = 3*). The values followed by different lowercase letters are significantly (P<0.05) different between groups. The absence of lowercase letters means none are significantly (P<0.05) different between groups.

Comparison between nutrient management in experimental systems

Referring to IMTA systems, N- and P-intake were 1.25 and 1.98 g fish^{-1}, respectively (Table 5). The total N-retention and P-retention in IMTA systems were calculated to be 86 and 55%, respectively. However, for IMTA treatments, the highest N-retention gained was observed by tilapia (68%), followed by silver carp (14%), mullet (2.5%), freshwater mussels (0.9%), and crayfish (0.2%). Rice cultivated in FRS and NFT gained N-retention values of 9.6 and 1.3%. The total N-retention in IMTA-R-FRS and IMTA-R-NFT systems was 96 and 87%, respectively (Figure 7). The highest gain of P-retention was observed in silver carp (29%), tilapia (19%), mullet (6%), freshwater clams (2%), and crayfish (0.1%). For rice cultivated (R-FRS and R-NFT), FRS (5%) had the highest P-retention, followed by treatment NFT (0.7%). The total P-retention in IMTA-R-FRS and IMTA-R-NFT systems was 60 and 56%, respectively (Table 5). Thus, similar to IMTA, tilapia monoculture systems improved total N-retention and P-retention in tilapia bodies by 68 and 19%, respectively. Rice cultivated with FRS and NFT retained 2.3% and 0.2% of their N, and 1.3% and 0.1% of their P, respectively. Total N-retention and P-retention in T-R-FRS and T-R-NFT systems were found to be 70 and 68%, and 20 and 19%, respectively (Table 5 and Figure 7).

Discussion

Aquaculture and agriculture must grow sustainably while considerably decreasing their environmental consequences in increasing food production (Ahmed and Turchini, 2021). The current study's goal is to create integrated agriculture-aquaculture production systems in greenhouse environments by combining hydroponic techniques (FRS and NFT) with IMTA and rice (IMTA-R-FRS and IMTA-R-NFT) compared to monoculture tilapia-rice systems (T-R-FRS and T-R-NFT). However, the information on cultivating rice hydroponically using IMTA systems (IMTA-R-FRS, IMTA-R-NFT, T-R-FRS, and T-R-NFT) such as developed systems, information on the growth, yield, and productivity of rice and aquatic animals (vertebrates and invertebrates) is scarce.

In the current investigation, the average water values of TP, TN, and TAN in IMTA treatments (IMTA-R-FRS and IMTA-R-NFT) were lower than those in monoculture tilapia treatments (T-R-FRS and T-R-NFT) and may be due to the higher NUE and PUE in IMTA treatments (Nile tilapia, mullets, crayfish, freshwater mussels, and silver carp) compared to tilapia monoculture treatments. These data indicate that all rice characteristics are higher in the FRS-R-IMTA system than in the NFT system because the FRS system absorbs more N and P due to lower water flow. Likewise, the IMTA system produces more nitrogenous waste, which is beneficial to rice compared to monoculture system. In contrast, Frei and Becker (2005) found no significant differences in rice characteristics (yield of grain, straw, stem, leaf, number of panicles, and seeds per panicle) grown in integration with tilapia and carp, or with carp only, compared to rice grown alone, due to differences in experimental designs, experimental conditions, and different aquatic abiotic factors. The current study's findings, which were consistent with previous studies that evaluated various types of hydroponic components together, indicated that NFT systems were less effective in terms of overall production, growth, and yields when compared to other aquaponic systems (Lennard and Leonard, 2006).

Concerning climate adaptation approaches, IMTA-rice aquaponic systems and tilapia-rice monoculture systems have both demonstrated to reduce nutrient and water losses while increasing crop yields. They can also provide an extra source of income for farmers by selling both rice and aquatic animals to end customers. They enable the optimal use of water and nutrients and are promising approaches for optimizing WUE, NUE, and PUE efficiency (Reddy and Kishori, 2018).

The current results are in the same line with previous results reported by Li et al. (2019), who reported that the co-cultivating between rice-yellow catfish, *Pelteobagrus fulvidraco*, and rice-freshwater shrimp, *Macrobrachium nipponense* in the same pond reduced the nutrients (TP, TN, TAN, and total potassium), indicating that shrimp-rice integrated pond cultivation is a successful way to improve nutrient utilization efficiency. Frei and Becker (2005) observed similar trend results.

The higher (P≤0.05) rice yield was observed by IMTA-R-FRS (8.8 ton ha^{-1}) compared to other experimental treatments T-R-FRS (5.8 ton ha^{-1}), IMTA-R-NFT (4.9 ton ha^{-1}), and T-R-NFT (2.5 ton ha^{-1}) mainly depending on the co-culture hydroponic system. This finding was previously supported by several studies (Rothuis et al., 1999; Tarigan et al., 2021; Weimin, 2010). In India, Mohanty et al. (2004) reported the total yield of rice ranged from 3 to 3.6 ton ha^{-1} with a total final yield of aquatic animals ranging from 0.91 to 1.28 ton ha^{-1}. In Bangladesh, Gupta et al. (1997) recorded the overall production of rice ranged from 3.8 to 5 tons ha^{-1} and 0.12 to 0.62 ton ha^{-1} aquatic animals production. Purba (1998) reported in another integrated co-culture study in Indonesia that the overall yield of rice and fish was 7.8 tons ha^{-1} for rice and ranged from 0.08 to 0.63 ton ha^{-1} for fish.

Another advantage of using IMTA-R-developed treatments (IMTA-R-FRS and IMTA-R-NFT) over tilapia-R-developed treatments (T-R-FRS and T-R-NFT) is higher aquatic animal biomass gain and profitability. The rice final yields of the developed systems (IMTA-R-FRS, T-R-FRS, IMTA-R-NFT, and T-R-NFT) were 8.8, 5.8, 4.9, and 2.5 tons ha^{-1}, respectively, when compared to traditional rice cultivation in Egypt ranging from 6 to 8 tons ha^{-1} (Hussein et al., 2023), which is one of the targets to achieve for climate adaptation and mitigation.

An additional promising observation is that the apparent FCR values in the IMTA system (0.73) are better than (P≤0.05) those in the tilapia monoculture system (1.58). This means that the current IMTA-developed technology enables farmers to profitably raise a variety of aquatic animals without the use of costly extra feed.

Using IMTA-developed treatments (IMTA-R-FRS and IMTA-R-NFT) has an N- and P-retention advantage to tilapia-rice monoculture (T-R-FRS and T-R-NFT). These results revealed that the developed IMTA treatments (IMTA-R-FRS and IMTA-R-NFT) are more efficient in nutrient removal efficiency than tilapia monoculture treatments (T-R-FRS and T-R-NFT). This outcome can be attributed to the synergy of different feeding habits of aquatic animals in the IMTA system (mullet, crayfish, clams, and silver carp), which significantly boosted the N and P removal utilization efficiency (Otazua et al., 2022). Tarigan et al. (2021) reported an increase of P (18%) and N (10%) in freshwater rice-fish integrated aquaponics systems.

Conclusions

The present study highlights the importance of adopting and developing integrated agriculture aquaculture systems that represent a possible strategy to cope with climate changes in both developing and developed countries. In addition, the integrated rice-IMTA-aquaponic and rice-tilapia-aquaponic employing the FRS technique are more promising than NFT strategies for optimizing WUE, NUE, and PUE efficiency, guarantee food security and provide a more sustainable and resilient food production system. Furthermore, the rice-IMTA co-culture system was more sustainable than rice-tilapia-monocultures in terms of organic matter recycling and the reuse of waste products (nitrogen and phosphorus) from the growing aquatic species. However, IMTA has a higher rate of nutrient removal than monoculture. However, more research, particularly on the feasibility and usability of integrated rice-IMTA-aquaponics and rice-tilapia-aquaponics, is recommended

Acknowledgment

The current experiment was conducted at the El-Kanater El-Khayria fish station, National Institute of Oceanography and Fisheries (NIOF), Kalubiya Governorate, Egypt as part of the research project work plan (HortiMED Project) funded by the PRIMA program supported by the European Union's Horizon 2020 research and innovation program, grant number 1915. The contents of this publication are the sole responsibility of the authors and the PRIMA Foundation is not responsible for any use that may be made of the information it contains. Open access funding was provided by The Science, Technology and Innovation Funding Authority (STDF) in cooperation with The Egyptian Knowledge Bank (EKB). This research was partially supported by Chiang Mai University.

Ethical approval

The experiments presented in this manuscript were subjected to the general protocol standards for the Institutional Animal Care and Use Committee of the National Institute of Oceanography and Fisheries.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability statement

The authors confirm that the data supporting the findings of this study are available upon reasonable request from the corresponding author.

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Received: 23 VI 2024
Accepted: 9 I 2025