Sains Malaysiana 53(4)(2024): 747-757
http://doi.org/10.17576/jsm-2024-5304-02

Aquaponics vs Recirculating Aquaculture System: Assessing Productivity and Water Use Efficiency of Native Fish Species *Empurau* (*Tor tambroides*) and *Jelawat* (*Leptobarbus hoevenii*) Compared to Red Hybrid Tilapia

(Akuaponik vs Sistem Akuakultur Kitar Semula: Menilai Produktiviti dan Kecekapan Penggunaan Air Spesies Ikan Asli Empurau (*Tor tambroides*) dan Jelawat (*Leptobarbus hoevenii*) Berbanding Tilapia Hibrid Merah)

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Received: 25 August 2023/Accepted: 26 February 2024

ABSTRACT

A 3 × 2 (fish species × culture system) factorial design experiment was conducted to compare productivity of *empurau* (*Tor tambroides*), *jelawat* (*Leptobarbus hoevenii*) and red hybrid tilapia (*Oreochromis* sp., control) cultured in recirculating aquaculture system (RAS) and aquaponics system. Growth performance, feed conversion ratio (FCR) and survival rate of fish were evaluated, and water quality of all tanks throughout the 70-days experiment was determined. In the present study, FCR of tilapia, *empurau* and *jelawat* tended to be lower in aquaponics than RAS, while no significant differences (P>0.05) on weight gain (WG) and specific growth rate (SGR) between RAS and aquaponics for each fish species were observed. Although tilapia had significantly higher WG and SGR, and lower FCR compare to *empurau* and *jelawat*, the survival rate of *empurau* and *jelawat* were higher than tilapia, regardless of the culture system. Between *empurau* and *jelawat,* better growth performance was observed in aquaponics than in RAS. Significantly higher (p<0.05) ammonia and nitrite concentrations were shown in RAS tanks as compared to aquaponics tanks, regardless of the fish species. *Jelawat* might have wide range tolerance to ammonia as no mortality in both RAS and aquaponics, while tilapia and *empurau* had higher survival rate in aquaponics than RAS. In summary, aquaponics appears to be a viable approach to enrich variety and improve fish production in an environmentally responsible manner. Therefore, it is plausible to advocate for the use of aquaponics as a sustainable methods of farming native fish species in Malaysia.

Keywords: Aquaponics; native fish species; recirculating aquaculture system; red hybrid tilapia

ABSTRAK

Suatu kajian reka bentuk faktorial 3 × 2 (jenis ikan × sistem kultur) telah dijalankan untuk membanding produktiviti empurau (*Tor tambroides*), jelawat (*Leptobarbus hoevenii*) (jelawat), dan tilapia hibrid merah (*Oreochromis* sp., sebagai kawalan) yang dibiak dalam sistem akuakultur kitar semula (RAS) dan sistem akuaponik. Prestasi tumbesaran, nisbah penukaran makanan (FCR), dan kadar kemandirian ikan telah dinilai. Kualiti air dalam semua tangki sepanjang tempoh 70 hari juga telah ditentukan. Dalam kajian ini, FCR tilapia, empurau dan jelawat adalah lebih rendah dalam sistem akuaponik berbanding dengan RAS. Sementara itu, tiada perbezaan signifikan (P> 0.05) dalam penambahan berat (WG) dan kadar tumbesaran khusus (SGR) antara RAS dan akuaponik bagi setiap spesies ikan. Walaupun tilapia menunjukkan WG dan SGR yang lebih tinggi secara signifikan, FCR tilapia didapati lebih rendah daripada empurau dan jelawat. Kadar kemandirian empurau dan jelawat didapati adalah lebih tinggi daripada tilapia dalam kedua-dua sistem kultur. Antara ikan empurau dan jelawat, prestasi tumbesaran yang lebih baik diperhatikan dalam sistem akuaponik berbanding RAS. Kandungan ammonia dan nitrit yang lebih tinggi secara signifikan (p<0.05) telah diperhatikan dalam RAS berbanding sistem akuaponik, tanpa mengira jenis spesies ikan. Jelawat mungkin mempunyai julat toleransi ammonia yang tinggi kerana tiada kematian dalam kedua-dua sistem RAS dan akuaponik diperhatikan. Tilapia dan empurau mempunyai kadar kemandirian yang lebih tinggi dalam sistem akuaponik berbanding dengan RAS. Kesimpulannya, akuaponik merupakan sistem kultur yang berpotensi untuk mempelbagaikan ikan tempatan dan meningkatkan pengeluaran ikan dengan cara mesra alam. Oleh itu, penggunaan sistem akuaponik sebagai salah satu sistem penternakan yang mampan untuk pembiakan spesies ikan asli di Malaysia adalah amat digalakkan.

Kata kunci: Akuaponik; sistem akuakultur kitar semula; spesies ikan asli; tilapia hibrid merah

INTRODUCTION

Aquaponics, an agricultural practice that integrates aquaculture and hydroponic in a farming system to produce fish and crop, is an emerging agricultural practice that is gaining popularity globally. It grows aquatic organisms as well as agricultural crops in a farming system, creating a symbiotic environment (Yep & Zheng 2019). Modern aquaponics works by channelling the waste water that contains metabolic products and uneaten feeds from the aquaculture tank, and utilizing the effluent as a nutrient source through nitrification to grow the crops planted in the hydroponic section. The effluent is then recycled as clean water and returned to the aquaculture tank which conserves water for a sustainable fish cultivation.

Water conservation to secure water resources is one of the challenges in aquaculture (FAO 2017), while improving food productivity to achieve zero hunger is also essential to achieving the sustainable development goals listed by the United Nations. Concerns regarding resource scarcity and food safety are raised by Dinar et al. (2019) and FAO (2017). Hence, aquaponics is extensively adopted for fish and crop cultivation, mainly due to its great deal of advantages such as high water efficiency (Yep & Zheng 2019), producing more than one type of food in a system (Lennard & Goddek 2019), reducing the release of waste water into the environment and mitigating negative environmental impacts caused by conventional aquaculture farms (Estim et al. 2023; Suárez-Cáceres et al. 2021). Aquaponics' advantages could propel this method toward sustainable agriculture as a technology-intensive breakthrough (FAO 2020).

Aquaponics have also been reported in improving the growth performance and survival rate of fish as compared to conventional aquaculture using recirculating aquaculture system (RAS). Particularly, previous studies have reported that Nile tilapia (*Oreochromis niloticus*) grown in aquaponics showed better survival rate and growth performance due to enhanced water quality including higher dissolved oxygen (DO), lower total ammonia nitrogen (TAN) and nitrite concentrations compared to RAS (Effendi, Wahyuningsih & Wardiatno 2017; Setiadi, Widyastuti & Prihadi 2018). Likewise, rainbow trout (*Oncorhynchus mykiss*) cultured in aquaponics also showed a lower feed conversion ratio (FCR) and higher specific growth rate (SGR) than those grown in RAS (Atique, Lindholm-Lehto & Pirhonen 2022).

However, only a few fish species, particularly tilapia, have been observed to be popular in aquaponics (Love et al. 2015; Mchunu, Lagerwall & Senzanje 2018; Pattillo et al. 2022; Villarroel et al. 2022). Ornamental fish and catfish are other fish species that are commonly cultivated in aquaponics (Love et al. 2015; Pattillo et al. 2022). Additionally, crop production in aquaponics is more profitable than fish production in aquaponics as Bosma et al. (2017) reported that an aquaponics farm that primarily cultured low-value fish species like tilapia could not be successful in Philippines. Aquaponics farms could not run profitable operations if they only sell fish species with a low market value. Besides, in many locations, tilapia and catfish are exotic fish species that may not be well accepted for consumers in all markets, as such, native fish species appears be a viable option for meeting local market demand and increasing the variety of fish in aquaponics (Pinho et al. 2021). Adoption of native species in aquaponics can help to promote them into the international market and boost aquaculture production diversity.

Although local fish species have great production values in Malaysia, they are not commonly cultivated in aquaponics. Native fish species growing in aquaponics are not thoroughly researched, despite the fact that they could become an alternative to common fish species grown in aquaponics (Pinho et al. 2021). The selection of native fish species could be based on those with high market value and demand (Bosma et al. 2017), such as *empurau* (*Tor tambroides*) and *jelawat* (*Leptobarbus hoevenii*) in Malaysia (Amirrudin & Zakaria-Ismail 2014; Department of Fisheries 2022; Lau et al. 2023). Growing native fish species could also help to prevent the spread of exotic species, which could endanger the native population in the wild, as tilapia (*Tilapia nilotica*) was described as an introduced species that invaded the nation's local streams (Ahmad et al. 2020). Therefore, a factorial design 3 × 2 (species × culture system) experiment was conducted to investigate the growth performance, survival rate and FCR of *empurau*, *jelawat* and the most popular aquaponic fish species, red hybrid tilapia (*Oreochromis* sp.) cultured in aquaponics as compared to the RAS system, with the goal of determining the viability of native fish species, *empurau* and *jelawat* produced in aquaponics. Water qualities and water use efficiency were also examined among different fish species cultured in the two experimental culture systems.

MATERIALS AND METHODS

EXPERIMENTAL SETUP

Aquaponics systems were setup (Figure 1, modified from Effendi, Wahyuningsih & Wardiatno 2017; Setiadi, Widyastuti & Prihadi 2018) and placed in the Aquaculture Facilities (AQF), Universiti Tunku Abdul Rahman (UTAR). Glass tanks with 90 L capacity each (30 × 70 × 46 cm^3) were used as the fish tank and hydroponic tank in the aquaponics system. For aquaponics system, the water was channelled from the fish tank to the filtering section consisting of mechanical (cotton and sponge filter) and biological filters (ceramic rings and bio balls) for large residue removal and nitrification. Then, the water was flown to the hydroponic tank and pumped back to the fish tank. Two units of water pump (7-Watt, maximum water flow 570 L/hour) were installed at the fish and hydroponic tanks each. Air stones were provided for both fish and hydroponic tanks to increase the DO. RAS setup was similar with the aquaponics system excluding the hydroponic tank and the water was recycled between the fish tank and filtering section.

FISH AND CROP CULTIVATION

Three experimental fish species were *empurau*, *jelawat* and red hybrid tilapia (control fish species). There were a total of six treatments: aquaponics culturing red hybrid tilapia, aquaponics culturing *empurau*, aquaponics culturing *jelawat*, RAS culturing red hybrid tilapia, RAS culturing *empurau* and RAS culturing *jelawat* in triplicates each used in the present study. Fingerlings of each species were obtained from the local hatchery suppliers. Upon arrival, fishes undergone acclimation for one month with twice feeding daily in the AQF before the commencement of cultivation experiment. Commercial nitrifying bacteria (Qiuyu, 2 capsules) were added into both aquaponics and RAS tanks a week prior to the experiment to kick start the nitrifying process immediately. Fish stocking density was fixed at 4 fish/90 L (Saufie 2020; Setiadi, Widyastuti & Prihadi 2018), for each species, four healthy and similar size fish were selected and distributed into their respective tanks. At the commencement of cultivation experiment, the initial weight of the fishes was recorded in which 2.80 ± 0.04 g for red hybrid tilapia, 2.63 ± 0.04 g for *empurau* and 2.68 ± 0.05 g for *jelawat*. Initial water quality parameters were also recorded for both RAS and aquaponics. Commercial fish pellet with 35% crude protein and 1.5 mm diameter (Cargill, AquaFocus Prestarter 6383) was used as experimental feed. Fishes were fed until apparent satiation twice per day (09:00 and 17:00 h) for 70 days. Besides, the water quality parameters were monitored (Tawaha et al. 2021) throughout the experiment. Weekly water change was done to all RAS tanks to maintain its water quality; for aquaponics tanks, water was added to offset the evapotranspiration loss.

Bak choy (*Brassica rapa*) was cultured as the experimental crop in the present study. Seed of the *bak choy* was germinated on the germinating sponge and grown for three weeks before transplanting into the hydroponic section for each experimental aquaponics tank. Deep water culture (DWC) was used whereby roots of the seedlings were submerged into the culture water for nutrient absorption. Transplantation of *bak choy* seedlings were done three weeks after fish distribution into the experimental tank. Fish to plant ratio was set as 1:1, hence, each aquaponics consisted of four *bak choy* seedlings in total. Hydroponic fertilizer (CityFarm Malaysia, hydroponic AB liquid fertilizer) consisting of nitrogen (22.5%), phosphorus pentoxide (9%), potassium oxide (37%), calcium oxide (26%), magnesium oxide (3%), sulphur oxide (13%), boron (0.02%), copper-ethylenediaminetetraacetic acid (EDTA, (0.004%), iron-EDTA (1.32%), iron-diethylenetriamine pentaacetate (DPTA, 0.14%), iron- ethylenediamine-*N*,*N*'-bis(2-hydroxyphenylacetic acid) (EDDHA, 0.01%), manganese-EDTA (0.033%), molybdenum (0.003%) and zinc-EDTA (0.021%) was supplemented to provide adequate nutrients for the plants grown in aquaponics (Fischer et al. 2021; Meena et al. 2023; Monsees, Kloas & Wuertz 2017; Tawaha et al. 2021; Villarroel et al. 2022; Yep & Zheng 2019). Fertilizer supplement was applied whenever signs of nutritional deficiency were observed on the crops grown in aquaponics. Each aquaponics system was equipped with a commercial plant grow light LED lamp (48:24, white:red) with a photosynthetic photon flux (PPF) of 200 mol/s and a 12-h photoperiod.

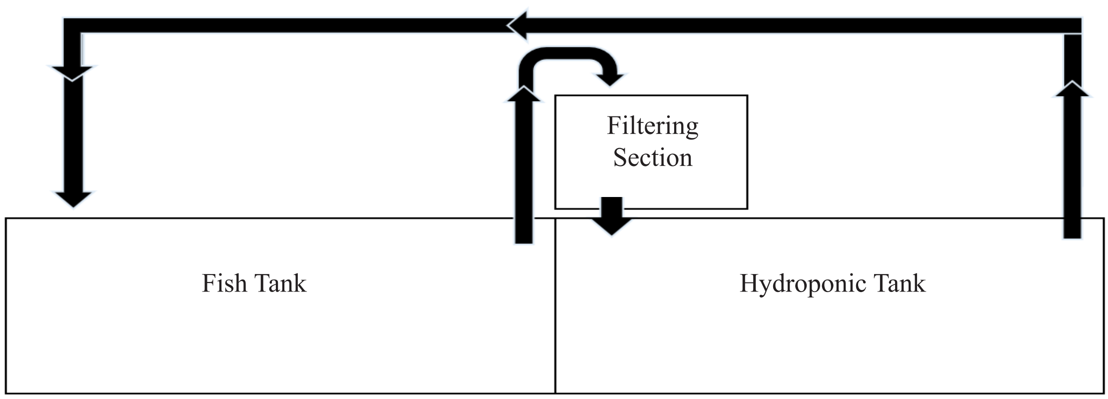

FIGURE 1. Front view of the aquaponics system setup. Black arrows indicate the water flow of the whole system

DATA COLLECTION

After 70 days of cultivation, all experimental fishes were individually weighed. Fish growth performance was analysed based on weight gain (WG, %) and specific growth rate (SGR, %/day) of fish. Fish survival rate (%) and FCR were also evaluated for all experimental treatments (Effendi, Wahyuningsih & Wardiatno 2017; Tawaha et al. 2021). The formulae used are shown as follows:

$$\text{WG (\%)} = \frac{\text{Final wet weight (g) - Initial wet weight (g)}}{\text{Initial wet weight (g)}} \times 100\%$$

$$\text{SGR} = \frac{\ln[\text{final wet weight (g)}] - \ln[\text{initial wet weight (g)}]}{\text{Duration (days)}} \times 100\%$$

$$\text{Survival rate (\%)} = \frac{\text{Final number of fish}}{\text{Initial number of fish}} \times 100\%$$

$$\text{FCR} = \frac{\text{Total feed given in dry weight (g)}}{\text{Total wet weight gain of fish (g)}}$$

Measurements of the physical and chemical water quality parameters were carried out throughout the experiment. Water temperature (ºC), pH and dissolved oxygen (DO, mg/L) were measured on daily basis using potable pH meter (HI8424, HANNA instruments, USA) and portable DO meter (ECDO1101, EUTECH, Singapore). Chemical water parameters including ammonia-nitrogen (NH_3-N), nitrite (NO_2^-) and nitrate (NO_3^-) were measured in mg/L every three days using API freshwater master test kit, and the data were validated using multiparameter spectrophotometer (HI83399, HANNA instruments, USA) once a week or when the concentration exceeded detection limit of the test kit; while phosphate (P), potassium (K), calcium (Ca), magnesium (Mg) and iron (Fe) were measured in mg/L on a biweekly basis for each treatment using the same multiparameter spectrophotometer (Tawaha et al. 2021). Weekly and total water usage (L) for all experimental tanks were recorded for water efficiency comparison.

Within 70 days of fish cultivation, two batches of *bak choy* were planted and harvested at 35 days interval in aquaponics treatments, and the total supplementation of fertilizer (mL) was recorded. After harvested, the plant roots were removed before weighing. Fresh crop yield (g) was determined by measuring total fresh weight (g) of the *bak choy* harvested from each aquaponics treatment, including the stem and leaves (Effendi, Wahyuningsih & Wardiatno 2017), and relative growth rate (%) of the *bak choy* was evaluated with the formula shown herewith:

$$\text{Relative growth rate (\%)} = \frac{\ln[\text{final wet weight (g)}] - \ln[\text{initial wet weight (g)}]}{\text{Initial number of fish}} \times 100\%$$

STATISTICAL ANALYSIS

All data were presented as mean ± standard deviation. Statistical analysis was conducted using SPSS 27.0 (SPSS Inc., Chicago, USA). T-test was used to analyze the difference in initial water quality between RAS and aquaponics systems. Data were subjected to Shapiro-Wilk test for normality before being analysed through analysis of variance (ANOVA). One-way ANOVA was used to determine if significant differences occurred on the nutrient supplementation, crop yield and relative growth rate of *bak choy* across aquaponics treatments. Two-way ANOVA was applied to determine the effects of fish species, culture method and their interaction in final fish body weight, WG, SGR, survival rate and FCR of the fishes, the water quality parameters and water usage across all experimental treatments. Differences among means were determined by Duncan's Multiple Range test and considered to be significant at the level of 0.05.

RESULTS AND DISCUSSION

FISH GROWTH PERFORMANCE, SURVIVAL AND FCR

In the present study, tilapia, *empurau* and *jelawat* grew over 1900%, 390% and 1100%, respectively, after 70 days of cultivation in the experimental tanks (Table 1). No significant differences ($P > 0.05$) were observed in the WG and specific growth SGR of the same fish species between aquaponics and RAS, indicating that fish yield produced by aquaponics is comparable to that of RAS. Comparing the three tested fish species, tilapia showed the significantly highest ($P<0.05$) WG (1925.27 - 2045.03%) and SGR (3.55 - 3.61%/day), while *empurau* showed the significantly lowest WG (390.99%) and SGR (1.87-1.88%/day). In a previous study, *empurau* cultivated for 14 weeks was reported to have a low SGR ranged between 0.31 and 0.51%/day (Misieng, Kamarudin & Musa 2011), which was profoundly lower than other tropical freshwater fish species such as tilapia and common carp (Kaushik 1998). However, the SGR of *empurau* cultured in either RAS (1.88%/day) or aquaponics (1.87%/day) in the present study was higher than those reported previously (Misieng Kamarudin & Musa 2011; Sulaiman et al. 2022). Likewise, the SGR of *jelawat* cultured in RAS (2.98%/day) and aquaponics (2.96%/day) were higher than that of *jelawat* (0.59-0.72%) cultured in a polyethylene tank without filtration (Farahiyah et al. 2017). Increased SGR of *jelawat* and *empurau* in the present study indicating the beneficial effect of using RAS and aquaponics systems in improving growth performance of these two native species.

On the other hand, fish grown in aquaponics tended to have higher survival rate than in those grown in RAS despite no significant difference was observed within the same fish species. This agrees with Fischer et al. (2021) and Wang et al. (2022) where fish survival rate was relatively higher in aquaponics compared to RAS although no difference on fish growth performance. Cultivation of *empurau* and *jelawat* with aquaponics also showed 100% survival which may be attributed to the better water quality (stable water pH, and lower ammonia and nitrite concentrations) in the aquaponics systems. Meanwhile, tilapia cultured in RAS had the lowest survival rate (66.67%), while tilapia in aquaponics and *empurau* in RAS showed 83.33% and 91.67%, respectively. This may be attributed by significantly higher ammonia and nitrite concentrations in RAS tanks as compared to the same fish species cultured in aquaponics (Table 2). This indicates that aquaponics is capable of reducing ammonia and nitrite concentrations through its effective biofiltration, contributing to improved water quality and, consequently, higher fish survival rates (Wang et al. 2022). Besides, frequent cannibalism that was observed in the tilapia tanks might be a contributing factor to its inferior survival rate (Duk et al. 2017), implying the advantages of culturing *empurau* and *jelawat*.

Besides, fish grown in aquaponics tended to have lower FCR than those grown in RAS, although no significant difference was recorded between the systems for same fish species (Table 1). Similar finding was reported by Effendi, Wahyuningsih and Wardiatno (2017), Fischer et al. (2021) and Oladimeji et al. (2020). This may be attributed to the higher ammonia concentration in RAS that induces fish stress response which is energy demanding (Paust, Foss & Imsland 2011). Fish grown in RAS might consume more feeds which were utilized for stress responses triggered by poor water quality rather than weight gain, resulting in higher FCR as compared to those cultured in aquaponics. Moreover, tilapia showed the lowest FCR either cultured in RAS (1.27) or aquaponics (1.13) among the three fish species (Table 1), which was lower than that reported in previous studies where a FCR of 2.02 shown in RAS and a range of 1.60-1.70 in aquaponics (Effendi, Wahyuningsih & Wardiatno 2017), while a FCR ranged 1.14-1.27 has also been reported for tilapia cultured in aquaponics by Tawaha et al. (2021). Among three fish species, the significantly highest FCR were recorded in the *empurau* tanks either RAS (2.62) or aquaponics (2.30), which were within the range of 2.13-3.26 reported in previous studies (Misieng, Kamarudin & Musa 2011; Ng, Abdullah & De Silva 2008; Sulaiman et al. 2022). Besides, FCR of *jelawat* cultured in aquaponics (1.68) was better than that of those grown in a polyethylene tank without a RAS or an aquaponics system, which ranged from 1.70 to 2.18 (Farahiyah et al. 2017). Put simply, aquaponics could improve FCR of fish, with the benefit being more profound over a longer cultivation period.

WATER QUALITY PARAMETERS AND WATER USAGE

The water quality parameters of all treatment tanks were presented in Table 2. Significant difference was observed in the temperature of initial water in which aquaponics tanks (27.65 ± 0.31 °C) had higher temperature than RAS tanks (27.00 ± 0.13 °C) (Table 3) because of the LED lamps in the aquaponics and the lower positioning of the RAS tanks. Yet, throughout the cultivation experiment, the difference in water temperature had no impact on the growth of fishes and crops as the temperature was within the range reported in the earlier studies (Junaid et al. 2023; Ogah et al. 2020). There was no significant difference found in DO across all the treatment tanks (6.82 mg/L to 7.11 mg/L), however, there were significant differences in the pH between RAS (5.94 - 6.14) and aquaponics (6.44 - 6.73) systems. Aquaponics also resulted in a more constant water pH with a lower standard deviation than RAS (Table 2). The reason for a more neutral and stable water pH could be attributed by the presence of crop plants that buffered the pH of the culture water in aquaponics by exchanging the ions of hydrogen and hydroxide in their roots during nitrate absorption (Makhdom, Shekarabi & Shamsaie Mehrgan 2017).

Throughout the cultivation experiment, higher ammonia (ranging from 0.40 to 1.17 mg/L) was found in the RAS tanks than in aquaponics, demonstrating the role of aquaponics in ammonia removal for improved water quality for fish growth. High ammonia concentration causes the reverse diffusion of ammonia molecules from the culture water into the blood that inhibits the excretion of ammonia from the fish body (Hargreaves & Kucuk 2001). This induce stress responses in the fish which are energy demanding, competing the energy consumption that is normally used for fish growth, ingestion and digestion (Paust, Foss & Imsland 2011). Rahmati, Hassan and Abdi (2022) also reported that increased ammonia concentration has significantly increased fish cortisol and glucose levels which led to death in tilapia. Furthermore, there was no mortality in *jelawat* regardless of cultivation system, despite the ammonia concentration was significantly higher in RAS (0.53 mg/L) than in aquaponics (0.00 mg/L). This suggests that *jelawat* has a higher tolerance to ammonia than tilapia. Previous study also reported that *jelawat* could grow in water containing up to 2 ppm ammonia with a 99.52% survival rate (Kamarudin, Idris & Toriman 2013). Although the nitrite concentration in RAS tanks (0.04 – 0.07 mg/L) was noticeably higher than in aquaponics (0.00 – 0.02 mg/L), yet it was below the lethal level (20 mg/L) that cause adverse effects to the fish's haematological properties, antioxidant defenses and stress responses (Kim, Kang & Lee 2022).

TABLE 1. Growth performance, FCR and survival rate of the three fish species cultured in RAS and aquaponics after 70 days of experiment

Fish Species	Tilapia		Empurau		Jelawat		Two-way ANOVA		
Type of System	RAS	Aquaponics	RAS	Aquaponics	RAS	Aquaponics	Type of system	Fish species	Interaction
Initial weight, (g)	2.67 ± 0.04	2.66 ± 0.05	2.62 ±0.04	2.65 ± 0.05	2.68 ± 0.05	2.68 ± 0.05	0.69	0.49	0.93
Final weight, (g)	59.78 ± 19.29^{c}	56.86 ± 15.79^{c}	12.81 ± 1.98^{a}	13.01 ± 3.14^{a}	33.02 ± 4.43^{b}	32.53 ± 4.90^{b}	0.83	<0.05	0.97
WG (%)	2045.03 ± 716.80^{c}	1925.27 ± 559.95^{c}	390.99 ± 80.47^{a}	390.99 ± 115.71^{a}	1134.89 ± 195.05^{b}	1111.84 ± 162.79^{b}	0.80	<0.05	0.96
SGR (%/ day)	3.61 ± 0.37^{c}	3.55 ± 0.34^{c}	1.88 ± 0.20^{a}	1.87 ± 0.28^{a}	2.98 ± 0.19^{b}	2.96 ± 0.17^{b}	0.82	<0.05	0.99
Survival rate (%)	66.67 ± 38.18^{a}	83.33 ± 14.43^{a}	91.67 ± 14.43^{a}	100.00 ± 0.00^{a}	100.00 ± 0.00^{a}	100.00 ± 0.00^{a}	0.34	0.07	0.72
FCR	1.27 ± 0.01^{a}	1.13 ± 0.07^{a}	2.62 ± 0.29^{c}	2.30 ± 0.24^{c}	1.74 ± 0.08^{b}	1.68 ± 0.12^{b}	0.11	<0.05	0.55

Data are presented in mean ± standard deviation. Different superscripts in the same row indicate significant difference at P<0.05

TABLE 2. Physical and chemical water parameters in experimental RAS and aquaponics tanks throughout the experiment

Fish species	Tilapia		*Empurau*		*Jelawat*		Two-way ANOVA		
System	RAS	Aquaponics	RAS	Aquaponics	RAS	Aquaponics	Type of system	Fish species	Interaction
Temperature (∘C)	26.88 ± 0.77^{a}	27.35 ± 1.07^{b}	27.02 ± 0.77^{a}	27.55 ± 0.96^{bc}	26.97 ± 0.80^{a}	27.55 ± 0.93^{bc}	<0.05	0.30	0.84
pH	6.06 ± 0.31^{ab}	6.44 ± 0.09^{bcd}	5.94 ± 0.35^{a}	6.59 ± 0.07^{cd}	6.14 ± 0.34^{abc}	6.73 ± 0.15^{d}	<0.05	0.10	0.35
DO (mg/L)	6.82 ± 0.64^{a}	6.91 ± 0.49^{a}	7.11 ± 0.27^{a}	6.98 ± 0.34^{a}	6.97 ± 0.36^{a}	7.05 ± 0.26^{a}	0.47	0.29	0.09
NH_3-N (mg/L)	1.17 ± 1.47^{c}	0.08 ± 0.39^{a}	0.40 ± 0.41^{ab}	0.02 ± 0.10^{a}	0.53 ± 1.03^{b}	0.00 ± 0.00^{a}	<0.05	<0.05	<0.05
NO_2^- (mg/L)	0.07 ± 0.07^{b}	0.02 ± 0.03^{ab}	0.05 ± 0.07^{b}	0.01 ± 0.03^{ab}	0.04 ± 0.05^{b}	0.00 ± 0.01^{a}	<0.05	0.27	0.81
NO_3^- (mg/L)	65.92 ± 48.05^{a}	71.08 ± 58.59^{a}	71.31 ± 46.48^{a}	72.98 ± 55.10^{a}	67.57 ± 44.92^{a}	68.77 ± 47.70^{a}	0.76	0.92	0.98
P (mg/L)	2.77 ± 2.35^{a}	2.97 ± 1.97^{a}	2.53 ± 1.36^{a}	2.05 ± 0.83^{a}	2.80 ± 1.82^{a}	2.16 ± 1.10^{a}	0.40	0.41	0.60
K (mg/L)	13.87 ± 4.47^{a}	22.68 ± 6.78^{c}	10.95 ± 3.26^{a}	17.94 ± 6.51^{b}	12.62 ± 3.11^{a}	18.88 ± 5.68^{bc}	<0.05	0.05	0.70
Ca (mg/L)	45.80 ± 29.11^{a}	70.13 ± 34.95^{a}	62.13 ± 40.23^{a}	65.87 ± 32.51^{a}	74.20 ± 36.41^{a}	63.00 ± 35.19^{a}	0.46	0.52	0.17
Mg (mg/L)	6.21 ± 3.28^{a}	7.14 ± 5.26^{a}	3.36 ± 3.58^{a}	6.00 ± 4.93^{a}	6.86 ± 4.16^{a}	6.86 ± 7.80^{a}	0.30	0.23	0.63
Fe (mg/L)	0.07 ± 0.03^{a}	0.11 ± 0.18^{a}	0.04 ± 0.01^{a}	0.05 ± 0.03^{a}	0.14 ± 0.22^{a}	0.06 ± 0.03^{a}	0.78	0.17	0.16

Data are presented in mean ± standard deviation. Different superscripts in the same row indicate significant difference at $P<0.05$

In the present study, K concentration in aquaponics was significantly higher than RAS regardless the fish species. Despite the addition of nutrients to the aquaponics, there was no significant effect on the concentration of NO_3^-, P, Ca, Mg, and Fe between RAS and aquaponics (Table 2). K, Ca, Mg and Fe are the limiting nutrients in aquaponics, which are essential for plant growth (Yang & Kim 2020; Yep & Zheng 2019). As a result, nutrient supplementation in aquaponics greatly increased the K content which could also help plants absorb other nutrients (Yep & Zheng 2019). This may explain why the P, Ca, Mg, and Fe concentrations in aquaponics were not significantly different with RAS (Table 2).

Besides, the total supplementation in aquaponics was found to be not significantly different across the three fish species (Table 4). The total fresh crop yield and relative growth rate of *bak choy* in aquaponics were also not significantly different among the fish species (Table 4). However, there was a big variation in each batch of crop yields and as some crops were infected by insect pests, including caterpillars and leaf miners. As no pesticides were used in this experiment, these pests were removed by hand on a daily basis. However, this manual method necessitates a great amount of effort, which might be a serious issue if a large aquaponics farm is in operation.

In addition, weekly and total water usage in RAS were significantly higher than aquaponics, for the three fish species (Table 5). Weekly water change was performed on the RAS tanks to lower the ammonia concentration and the significantly highest water usage was found in RAS culturing tilapia (292.80 L), followed by RAS culturing *jelawat* (230.40 L) and RAS culturing *empurau* (194.40 L), whereas only a range of 34.96 L to 37.96 L of water added to the aquaponics tanks throughout the cultivation period. Likewise, Yep and Zheng (2019) reported that aquaponics had a higher water use efficiency than RAS because it only needed 0.3 to 0.5% of total system water per day. Aquaponics enhances water use efficiency in fish farming through sustainable means (Suárez-Cáceres et al. 2021). This practice effectively mitigates the environmental consequences of aquaculture waste water discharge, while also promoting the recycling of water for both fish and crop cultivation in an eco-friendly way.

Referring to the system setups in the present study, aquaponics requires more capital and operating costs than RAS due to the additional hydroponic section in the aquaponics system. However, aquaponics produces more than one type of agricultural product (crops and fish), coupled with low water usage, which can save water while improving the farm's income by selling different agricultural products. In terms of labour requirements, RAS demands more labour since it requires close monitoring of water quality parameters unlike aquaponic system which has a more stable water quality. It is crucial to note that site-specific factors, such as climate, available resources, and market conditions, can significantly impact the cost-benefit dynamics of both aquaponics and RAS. Additionally, advancements in technology and system design may influence these considerations over time. Consulting with experts and conducting a thorough feasibility study based on the farm's capability and specific requirements is advisable before choosing to adopt between an aquaponics system and RAS.

TABLE 3. Initial water quality of RAS and aquaponics before the commencement of fish cultivation

System	RAS	Aquaponics
Temperature (◦C)	27.00 ± 0.13[a]	27.65 ± 0.31[b]
pH	6.78 ± 0.13[a]	6.92 ± 0.14[a]
DO (mg/L)	7.03 ± 0.33[a]	6.83 ± 0.31[a]
NH_3-N (mg/L)	0.00[a]	0.00[a]
NO_2^- (mg/L)	0.00[a]	0.00[a]
NO_3^- (mg/L)	12.45 ± 3.97[a]	12.41 ± 5.10[a]
P (mg/L)	0.56 ± 0.09[a]	0.75 ± 0.34[a]
K (mg/L)	9.89 ± 0.88[a]	12.33 ± 0.99[a]
Ca (mg/L)	8.11 ± 4.17[a]	8.67 ± 2.75[a]
Mg (mg/L)	3.67 ± 1.33[a]	4.50 ± 1.83[a]
Fe (mg/L)	0.04 ± 0.02[a]	0.05 ± 0.01[a]

T-test was used to analyze the difference between the initial water quality of RAS and aquaponics systems. Data are presented in mean ± standard deviation. Different superscripts in the same row indicate significant difference at $P<0.05$

TABLE 4. Nutrient supplement, crop yield and relative growth rate (%) of *bak choy* harvested from the experimental aquaponics system

Fish Variety	Tilapia	*Empurau*	*Jelawat*	P value
Nutrient supplement (mL)	169.81 ± 4.33[a]	173.32 ± 9.31[a]	171.26 ± 3.32[a]	0.86
First batch crop yield (g)	112.15 ± 10.06[a]	105.75 ± 46.30[a]	107.59 ± 13.61[a]	0.76
Second batch crop yield (g)	69.18 ± 28.79[a]	102.23 ± 22.74[a]	99.57 ± 39.13[a]	0.69
Total crop yield (g)	181.33 ± 12.38[a]	207.96 ± 11.78[a]	207.16 ± 12.76[a]	0.71
Average crop yield (g)	88.39 ± 29.12[a]	93.20 ± 47.77[a]	94.39 ± 31.81[a]	0.96
Relative growth rate (%)	6.04 ± 1.12[a]	5.85 ± 2.00[a]	6.25 ± 2.38[a]	0.91

Data are presented in mean ± standard deviation. Different superscripts in the same row indicate significant difference at P<0.05

TABLE 5. Weekly and total water usage (L) of RAS and aquaponics throughout 70 days of experimental cultivation

System	RAS			Aquaponics			Two-way ANOVA		
Fish Variety	Tilapia	*Empurau*	*Jelawat*	Tilapia	*Empurau*	*Jelawat*	Type of system	Fish species	Interaction
Weekly water usage (L)	32.53 ± 10.56[c]	21.60 ± 0.00[b]	25.60 ± 5.31[b]	4.14 ± 0.11[a]	3.88 ± 0.09[a]	4.22 ± 0.04[a]	<0.05	<0.05	<0.05
Total water usage (L)	292.80 ± 34.45[c]	194.40 ± 0.00[b]	230.40 ± 21.20[b]	36.23 ± 2.85[a]	34.96 ± 2.95[a]	37.96 ± 2.78[a]	<0.05	<0.05	<0.05

Data are presented in mean ± standard deviation. Different superscripts in the same row indicate significant difference at P<0.05

CONCLUSIONS

In summary, the growth performance of tilapia, *empurau*, and *jelawat* reared in aquaponics compared favorably to that in RAS, with no significant differences observed. While fish FCR was generally improved in aquaponics than in RAS, survival rates for tilapia and *empurau* were higher in the aquaponics. The advantages of aquaponics for fish cultivation extend to improved water quality, consistent pH level, and efficient water consumption when compared with RAS. Notably, even though tilapia exhibited superior growth rates and lower FCR, the application of aquaponics remains viable for cultivating Malaysian indigenous fish species like *empurau* and *jelawat*. This approach holds potential to enhance diversity and boost fish production sustainably. Therefore, promoting aquaponics as a sustainable approach for farming of Malaysian indigenous fish species is justifiable.

ACKNOWLEDGEMENTS

This study was financed by Universiti Tunku Abdul Rahman Research Fund (UTARRF) awarded to the corresponding author by the Institute Postgraduate Studies Research, UTAR, Malaysia (IPSR/RMC/UTARRF/2021-C2/T04).

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