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Pertumbuhan dan kinerja ekonomi ikan bandeng (*Chanos chanos*) pada Sistem IMTA-Padi [The Growth and economic performance of milkfish in the IMTA-paddy System]

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ABSTRACT | Optimizing species combinations is essential for enhancing the Integrated Multi-Trophic Aquaculture (IMTA) system for milkfish, especially in brackish water involving paddy plants. This research examines the percentage weight gain (PWG), daily weight gain (DWG), profitability, and benefit-cost (B/C) ratio of milkfish farming within the IMTA-Paddy system using three treatments with three replication: T1 (milkfish and paddy), T2 (milkfish, tiger prawns, and paddy), and T3 (milkfish, tiger prawns, mussels, and paddy) within a completely randomized design model. Thirty individuals of each aquatic species were stocked per tarpaulin pond along with 30 clumps of floating paddy. Milkfish were fed commercial feed three times daily over 80 days. Results showed that T3 had significantly higher body weight gain (BWG: 796.43%) and daily weight gain (DWG: 1.23 g/day) than T2 and T1. T3 also yielded the highest profit (IDR 89,483/kg) and benefit-cost ratio (BCR: 1.61), significantly outperforming T2 and T1. The inclusion of mussels, acting as an organic extractive species, contributed notably to the improved growth and economic performance of milkfish in T3. These findings underscore the importance of well-designed species integration in improving aquaculture productivity and sustainability, and provide a promising foundation for scaling up IMTA-Padi systems in brackish coastal areas of Indonesia.

Key words | Brackish water, integrated aquaculture, production, profitability, species combination

ABSTRAK | Kombinasi hewan akuatik perlu direkayasa dengan baik untuk mengoptimalkan sistem Akuakultur Multi-Trofik Terpadu (IMTA) untuk ikan bandeng, terutama di air payau yang melibatkan tanaman padi. Penelitian ini bertujuan untuk menganalisis persentase pertambahan berat (PPB), pertambahan berat harian (PBH), keuntungan, dan rasio manfaat-biaya (B/C) budidaya ikan bandeng dalam sistem IMTA-Padi. Tiga perlakuan diuji: T1 (ikan bandeng dan padi), T2 (ikan bandeng, udang windu, dan padi), dan T3 (ikan bandeng, udang windu, kerang, dan padi), masing-masing dengan tiga ulangan yang dirancang dengan model rancangan acak lengkap. Tiga puluh individu dari setiap spesies akuatik ditebar per kolam terpal bersama dengan 30 rumpun padi apung. Ikan bandeng diberi pakan komersial tiga kali sehari selama 80 hari. Hasil penelitian menunjukkan bahwa T3 memiliki persentase pertambahan berat (PPB: 796,43%) dan pertambahan berat harian (PBH: 1,23 g/hari) yang secara signifikan lebih tinggi daripada T2 dan T1. Secara ekonomi, T3 juga menghasilkan keuntungan tertinggi (Rp 89.483/kg) dan rasio manfaat-biaya (BCR: 1,61), jauh mengungguli T2 dan T1. Dimasukkannya kerang, yang bertindak sebagai spesies ekstraktif organik, memberikan kontribusi yang signifikan terhadap peningkatan pertumbuhan dan kinerja ekonomi bandeng di T3. Temuan ini memberikan landasan yang berharga untuk mengembangkan sistem IMTA-Padi di wilayah pesisir payau Indonesia, yang menyoroti pentingnya kombinasi spesies dalam meningkatkan produktivitas dan keberlanjutan akuakultur.

Kata kunci | Air payau, akuakultur terintegrasi, kombinasi spesies, profitabilitas, produksi

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INTRODUCTION

Co-culture or integrated aquaculture is a farming technique where aquatic animals (such as fish, shellfish, crab, and shrimps) are used in paddy cultivation. The technique is offers ecological, economic, and social benefits (Bashir *et al*., 2020; Mansour *et al*., 2022). At the present, integrated aquaculture of aquatic animals and paddy cultivation is mostly practiced in fresh water. On the other side, brackish water area in Indonesia is approximately 2.96 million hectares, where only 605.90 thousand hectares (20.5%) of which is explored (KKP, 2023). Several varieties of saline-tolerant paddy can be cultivated in brackish water ponds to be co-cultured with aquatic animals. Half of the world's population consume rice as staple food (Rahman & Zhang, 2023). In Indonesia, rice becomes a significant commodity. Agriculture and aquaculture are significant food support systems (Farrag *et al*., 2021) that can be further developed in brackish water aquaculture for optimal resource exploration.

As found by previous researchers, the population of phytoplankton increases when tiger prawns and paddy are co-cultured in brackish water ponds (Sahabuddin, *et al*., 2019). However, Hendrajat *et al.* (2020) reported low performance in tiger prawns production and recommended the need for aquaculture technology intervention to increase productivity. Unfortunately, information and knowledge of aquatic animals and paddy co-culture in brackish water remain limited. The production systems of aquatic animals and paddy should be further studied, particularly in region where rice is the staple food such as in Indonesia.

In Indonesia, 80% of brackish water cultivation is managed using traditional technology (Tarunamulia & Sammut, 2023) in the forms of monoculture and polyculture. This traditional approach offers reliable food supply and storngly contributes to the local and national economy. The traditional systems can be optimized by promoting more profitable practices. This research was performed to explore the Integrated Multi-Trophic Aquaculture (IMTA) system to develop a polyculture system (Laktuka *et al.*, 2023) by integrating multiple aquatic species with paddy in brackish water (IMTA-Paddy). This research might be the first documented scientific research that analyzed the combination of aquatic animals with paddy cultivation in brackish water aquaculture.

The selection of species for an Integrated Multi-Trophic Aquaculture (IMTA) system is a critical stage due to the multispecies nature of the system, even though the species chosen are highly flexible (Chopin *et al.*, 2012). The candidate species for IMTA should be selected based on the trophic differences, economic viability, adaptability, bioremediation potential, and compatibility (Thomas *et al.*, 2021; Zhang *et al.*, 2019). Those parameters are significant in Ecosystem Approach to Aquaculture (EAA) that focuses on providing sustainability, profitability, and multi-sectoral benefits (FAO, 2018). Deep comprehension of species combinations is crucial in the implementation of integrated aquaculture systems to fully utilize different trophic and spatial niches (Thomas *et al.*, 2021). The right combination of species can create a healthy ecosystem that supports increased aquaculture production (Mondal *et al.*, 2020; Wahab *et al.*, 2011) and minimizes antagonistic interactions, while maximizing synergistic relationships between species (Amoussou *et al.*, 2022).

In this research, different combinations of milkfish (*Chanos chanos*), tiger prawn (*Penaeus monodon*), mussel (*Glauconome virens*), and paddy (*Oryza sativa*) were engineered to be applied in the IMTA-Paddy system. These four species are commonly cultivated by fish farmers in Indonesia through monoculture and polyculture systems. Previous research have shown that each of these organisms can be used in the IMTA system (Anand *et al.*, 2018; Anh *et al.*, 2018; Li *et al.*, 2019; Zhang *et al.*, 2019).

This research specifically focuses on the use of milkfish which is widely cultivated by traditional fish farmers in Indonesia. Milkfish has fast growth rate, adaptability to feed, tolerance to salinity and temperature, high density, and disease resistance (Bagarinao, 1991; Juario *et al.*, 1984) that is ideal for integrated aquaculture in brackish water. This research examined the growth and economic performance of milkfish cultivation under the IMTA-Paddy co-culture system in three combinations: milkfish- paddy, milkfish- tiger prawns- paddy; and milkfish-tiger prawns- mussels-paddy.

MATERIAL AND METHODS

Location and duration of study

This experimental research was performed 12 weeks at traditional fish ponds in Lerang Village, Lanrisang District, Pinrang Regency, South Sulawesi Province, Indonesia (3.90528°S and 119.56661°E)

Experimental design

Milkfish, tiger prawns, and mussels were reared in 200 × 200 × 100 cm tanks made of bamboo, wood, and tarpaulin. Nine tanks for paddy cultivation of 100 × 100 cm size were made using bamboo, waring, soil, and palm fiber as the planting media. Juveniles of milkfish and tiger prawns with initial weights of 12.27 ± 0.11 g and 0.37 ± 0.04 g, respectively, were obtained from a nursery unit near the study site. Shells (*Glauconome virens)* with an initial weight of 30.98 ± 0.19 g were collected from the estuary of Lanrisang. These aquatic animals were acclimatized to the experimental conditions for 3 days. Furthermore, Inpari 34 Salin Agritan variety paddy seeds were sowed in the pond to reach a height of 17.8 ± 0.1 cm before being integrated with the aquatic animals.

In this field experimental research, a pilot-scale tarpaulin model in a pond was used in different treatments and combinations (Table 1). Three replications applied to all experimental units (Figure 1).

Table 1. Species combination treatments.

Treatments	Species combinations
T1	Milkfish, paddy
T2	Milkfish, tiger prawns, paddy
T3	Milkfish, tiger prawns, mussels, paddy

Figure 1. Unit experiment

Rearing management

Prior to the experiments, each tank was fertilized with 0.1 kg of urea and triple super phosphate (TSP) (Anand *et al*., 2018). The tanks were left undisturbed for 7 days to allow plankton to grow. Probiotics (20 mL per tank) were also applied at 10 days intervals to increase feed efficiency and maintain water quality (Mondal *et al*., 2020). Each experimental tank, containing 280 L of water, was stocked with 30 milkfish, 30 tiger prawns, and 30 mussels. Paddy was planted in 30 clumps in separate containers and then floated into the experimental tanks (Figure 2). This floating method has been widely applied to paddy cultivation (Kang *et al*., 2016; Srivastava *et al*., 2017).

For 80 days, milkfish were fed commercial feed with 5% of biomass three times a day at 6:00 am, 12:00 pm, and 6:00 pm (Biswas *et al*., 2019). The commercial feed contained 21% protein, 8% fat, 9% fiber, 9% ash, and 12% moisture. Water quality parameters (temperature, salinity, dissolved oxygen, and pH) were monitored daily using various instruments: a CE thermometer, an ATC hand refractometer, a Lutron DO-5509 dissolved oxygen meter, and a Lutron PH-201 pH meter, respectively. Ammonia levels were also regularly measured based on water samples collected at the beginning, during, and end of the experiment and analyzing them in the laboratory according based on the standard procedures outlined by the American Public Health Association (APHA, 2017).

Figure 2. Floating method of paddy.

Growth and economic performance evaluation

Milkfish were sampled every 10 days to measure the weight using a digital balance (Camry EHA401) with an accuracy of 0.01 g. Growth performance was assessed based on the percentage weight gain (PWG) and daily weight gain (DWG) based on the method proposed by Anand *et al*. (2018) as follows:

$$PWG = Wt/Wo \times 100\ \%$$

$$DWG = (Wt - Wo)\ /\ t$$

PWG: percentage weight gain (%); DWG:daily weight gain (g day^{-1}); Wt: mean final weight (g); Wo: mean initial weight (g); t:rearing duration in days.

In this research, basic economic analysis was administered to estimate the production costs, revenues, profits, and benefit-cost ratio for the three species combinations. Production costs consists of costs of fertilizers, probiotics, feeds, and seeds for milkfish, tiger prawns, mussels, and paddy. The production income was calculated by multiplying the production quantity by the price of each species, while the profit was determined using the method proposed by Anand *et al*. (2018) as follows:

$$P = (TI - TC)$$

$$BCR = (TI\ /\ TC)$$

P: profit (IDR); TI: total income (IDR); TC: total cost (IDR); BCR: benefit–cost rasio.

Statistical analysis

The data for growth, economic parameters, and water quality were presented as mean ± SD. The Shapiro-Wilk Test of Normality and the Test of Homogeneity of Variances using SPSS for Windows v.25.0 (SPSS Inc., Chicago, IL, USA) showed that all data were normally distributed and homogeneous ($p>0.05$). Furthermore, the PWG and DWG among the different species combinations were analyzed using one-way ANOVA and Tukey's test at significance level of 95% ($P<0.05$).

RESULTS

Growth performance

The growth performance of the milkfish in three species combinations during the culture period. Juvenile milkfish were initially stocked at an average weight range of 12.21 – 12.33 g ($p>0.05$) in all species combinations. After 80 days of rearing, the highest final weight was obtained in T3, followed by T2, and the lowest was in T1, with a significant difference ($p<0.05$) among three treatments. The highest PWG and DWG performance were observed in T3, which was significantly different from T2 and T1. However, there was no significant difference ($p>0.05$) in PWG and DWG between T2 and T1. PWG and DWG of milkfish in T3 were 54.36% and 0.1 g day^{-1} higher than T2, and 69.55% and 0.12 g day^{-1} higher than T1, respectively.

Table 2. Growth performance of milkfish with different treatments.

Growth performances	Species combinations		
	T1	T2	T3
Initial mean weight, Wo (g)	12.25 ± 0.10[a]	12.21 ± 0.12[a]	12.33 ± 0.08[a]
Final mean weight, Wt (g)	101.32 ± 0.66[c]	102.84 ± 0.38[b]	110.55 ± 0.40[a]
Percentage weight gain, PWG (%)	726.88 ± 8.08[b]	742.07 ± 5.67[b]	796.43 ± 6.32[a]
Daily weight gain (g day^{-1}), DWG (g day^{-1})	1.11 ± 0.05[b]	1.13 ± 0.05[b]	1.23 ± 0.04[a]

T1: milkfish-paddy; T2: milkfish-shrimp-paddy; T3: milkfish-shrimp-mussel-paddy); Values are expressed as mean ± standard deviation (SE) of three replicate ponds; Means with different superscripts in lined up differ significantly (p<0.05).

Table 3. Economic performance of milkfish with different treatments.

Economic performances	Species combinations		
	T1	T2	T3
Total cost, TC (IDR)	109,552 ± 154.00[c]	128,404 ± 407.49[b]	146,122 ± 950.08[a]
Total production, TP (g)	3,039 ± 19.95[c]	3.487 ± 46,66[b]	5,085 ± 57.10[a]
Total income, TI (IDR)	112,461 ± 738.15[c]	175,091 ± 1,733.99b[b]	235,605 ± 1,885.55[a]
Profit, P (IDR kg^{-1})	2,910 ± 605.49[c]	46,687 ± 1,618.61[b]	89,483 ± 1,404.45[a]
Benefit-cost ratio, BCR	1.03 ± 0.055[c]	1.36 ± 0.011[b]	1.61 ± 0.005[a]

T1: milkfish-paddy; T2: milkfish-shrimp-paddy; T3: milkfish-shrimp-mussel-paddy); Values are expressed as mean ± standard deviation (SE) of three replicate ponds; Currency mentioned is IDR Indonesia; Means with different superscripts in lined up differ significantly (p<0.05).

Economic performance

The economic performance of the IMTA-Paddy system, including total cost, production, income, profit, and BCR for three species combinations (Table 3).

The prices of milkfish, tiger prawns, and mussels are 37,000 IDR kg-1, 135,000 IDR kg-1, and 30,000 IDR kg-1, respectively and are affected market mechanism. The calculation excluded paddy since it had not been harvested by the end of the research. At the end of the research, all economic parameters were the highst in T3, followed by T2, and lowest in T1 with significant differences (p<0.05) in each species combination. The total cost in T2 was IDR 18,552 (17.2%) higher than in T1 species, while the total cost in T3 was IDR 17,718 (13.8%) and IDR 36,570 (33.4%) compared to T2 and T1. Total production in T2 was 448 g (14.7%) higher than in T1, while total production in T3 was 1,598 kg (45.8%) and 2,046 kg (67. 3%) higher than in T2 and T1.

The income, profit, and BCR followed cost and production trends that differed significantly (p<0.05) in each species combination. The income and profit in T2 increased by IDR 62,630 (55.7%) and IDR 43,777 (1,504.4%) from T1, respectively. Meanwhile, the income and profit in T3 increased by IDR 60,514 (34.6%) and IDR 42,796 (91.7%) of T2. When compared to T1, the income and profit in T3 species were much higher at IDR 123,144 (109.5%) and IDR 86,573 (2,975.0%), respectively.

Water quality parameters

The water quality parameters did not show significant differences (p>0.05) between treatments, except for ammonia (Table 4).

Table 4. Water quality parameters of IMTA-Paddy system with different treatments.

Water quality parameters	Species combinations		
	T1	T2	T3
Temperatures (C)	28.2 ± 1.39	28.2 ± 1.34	28.2 ± 1.27
Salinity (ppt)	12.3 ± 1.62	12.4 ± 1.34	12.4 ± 1.64
Dissolved oxygen (mg L^{-1})	6.2 ± 0.35	6.2 ± 0.43	6.3 ± 0.39
pH	6.9 ± 0.15	6.8 ± 0.17	6.9 ± 0.16
Ammonia (mg L^{-1})	0.0221 ± 0.0179[b]	0.0306 ± 0.0260[c]	0.0167 ± 0.0111[a]

T1: milkfish-paddy; T2: milkfish-shrimp-paddy; T3: milkfish-shrimp-mussel-paddy); Values are expressed by mean ± SD; The different superscript letters indicate significant differences (p<0.05) by Tukey's HSD; Parameters that were not marked with superscript showed no significant difference (p>0.05).

DISCUSSION

Growth performance

Milkfish has been a significant source of income for farmers in almost all coastal areas of Indonesia (Isroni *et al*., 2020; Riany *et al*., 2023). Milkfish is often referred to as the "fish of a million people" for its popularity and its high nutritional value at affordable price (Anand *et al*., 2018; Malle *et al*., 2019). This research introduces the combination of milkfish culture system with tiger prawn and mussel in paddy cultivation within a floating system in brackish water.

The growth performance of milkfish was found higher compared to previous observations. The percent weight gain (PWG) in this study was around 168.6% in 180 days of rearing in floating net cages, higher than the 168.6% reported by Muya & Manyala (2015). Similarly, the PWG of 441.7% in 45 days of rearing in brackish water ponds was higher than the observations reported by Sontakke & Haridas (2018). The growth performance as seen from daily weight gain (DWG) in this research was also higher than previous ones. Anand *et al*. (2018) reported a DWG of 0.89 g day^{-1} for milkfish polycultured with crabs, and Biswas *et al*. (2012) reported a DWG of 0.71 g day^{-1} for milkfish polycultured with tiger prawns, both within 180 days of rearing in brackish water ponds. However, Mondal *et al*. (2021) demonstrated a slightly higher DWG of 1.21 to 1.48 g day^{-1} when milkfish were reared polycultured with tiger prawns and mullet fish within longer rearing period of 240 days. The differences in growth performance may be attributed to lower nutrient loss in controlled scale conditions compared to uncontrolled scale conditions, as well as the species composition and interactions in the polyculture system, which can create an ecosystem conducive to growth (Thomas *et al*., 2021; Wahab *et al*., 2011).

In this research, the mean PWG and DWG of milkfish showed a positive linear trend as the number of fish in the combination increased. The presence and absence of tiger prawns and mussels affect the PWG and DWG of milkfish. When co-cultured with paddy

(T1), the PWG and DWG of milkfish were only 726.88 ± 8.08% and 1.11 ± 0.004 g day^{-1}, respectively (Table 2). However, when co-cultured with paddy and tiger prawns (T2), the PWG and DWG of milkfish increased by 54.36% and 0.10 g day^{-1}. Both of these growth performances further increased when milkfish were co-cultured with paddy, tiger prawns, and mussels (T3) with an increase in PWG of 69.55% and DWG of 0.12 g day^{-1}. This research has demonstrated that incorporating a combination of three or four species can enhance the weight gain and growth of milkfish. It is inferred that the presence of species from different trophic levels will lead to better production results.

Numerous research have shown that tiger prawns as benthic feeders in co-culture systems offers benefits as they consume fish faeces (Eldani & Primavera, 1981) and sink waste from feed residues (Simao *et al*., 2013) that negatively affect the water quality (Dauda *et al*., 2019; Nederlof *et al*., 2021). Similarly, mussels, as filter feeders, can absorb organic particles such as food residue and faeces in the water through a filtration mechanism (Chopin *et al*., 2012; Zhang *et al*., 2019). The presence of these two species may have contributed to maintaining water quality, which is essential for the growth of milkfish. In integrated multi-trophic aquaculture (IMTA) systems, nutrients produced by one species can be utilized by other species, reducing the release of nutrient waste into the environment (Chopin *et al*., 2012; Nederlof *et al*., 2021). This ensures that the water quality meets the specific requirements of each cultivated species, making it an advantage of the IMTA system.

Mussels appear showed the most positive impact on the growth of milkfish in T3. The mussel species *G. virens* acts as a filter feeder that absorbs suspended particles at the bottom of the water (Brewer & Willan, 2018; Yap *et al*., 2009; Zakri & Mohamed, 2020). This species significantly reduced the concentration of ammonia (NH_3) which maintained the water quality (Table 4). Likewise, Lander *et al*. (2013) found that suspension feeder organisms should be included in the IMTA system to manage the suspended material in the rearing media.

Residual feed and faeces from milkfish, tiger prawns, and mussels contain nitrogen and phosphate, which can trigger the growth of natural food such as plankton and *klekap* (lab-lab) (Nederlof *et al*., 2021). The growth of *klekap* as the preferred food of milkfish was also observed in this research (Widianingsih *et al*., 2016). More optimal milkfish growth can be achieved through the supplementation of artificial feed into the natural food (Anand *et al*., 2018). The availability of natural food, in addition to sufficient artificial feed have contributed to the performance of milkfish in terms of PWG and DWG, as they are herbivorous fish (Bagarinao, 1991; Yap *et al*., 2007).

IMTA practice improves aquaculture performance by allowing different species to coexist and interact based on their compatibility and complementarity (Anand *et al*., 2018; Mondal *et al*., 2020; Thomas *et al*., 2021). In this research, milkfish occupied the water column, tiger prawns and mussels inhabited the bottom, and paddy was arranged to float on the surface. Although both mussels and tiger prawns share the benthic zone, their differing mobility-mussels being sessile and tiger prawns motile-minimizes spatial competition. The floating paddy further optimized ecological space use. Additionally, all four species occupied distinct trophic niches, enabling efficient nutrient utilization. Nutrient waste consists of particulate (organic) matter from faeces and uneaten feed, and dissolved (inorganic) compounds from excretion and feed decomposition (Dauda *et al*., 2019; Nederlof *et al*., 2021).

Tiger prawns and mussels excrete feces and metabolic waste (Pantjara *et al*., 2021; Srisunont & Babel, 2015). Tiger prawns as benthic species consume the leftover feed and feces that settle to the bottom of the waters (Eldani & Primavera, 1981; Simao *et al*., 2013). The shellfish *G. virens* as a filter feeder absorbs suspended feed and fecal particles through a filtration process (Srisunont & Babel, 2015; Zhang *et al*., 2019). Paddy with the floating method can effectively assimilate inorganic nutrients through its roots (Li *et al*., 2019; Srivastava *et al*., 2017). Therefore, this research confirms that milkfish, tiger prawns, mussels, and paddy are compatible and complementary species for co-culturing in brackish water.

Co-culturing milkfish, tiger prawns, mussels, and paddy through the IMTA system is a viable alternative for aquatic food production. Species combination affects the growth of milkfish, where the growth performance can be improved through co-culture with tiger prawns, mussels, and paddy in brackish water. The growth of tiger prawns and paddy improved within the combination of species. The findings of this research could serve as a basis for the profitable and sustainable cultivation of milkfish with tiger prawns, mussels, and paddy in coastal areas.

Economic performance

Economic performance analysis is a crucial management tool for evaluating the efficiency of resource allocation, profitability and sustainability of aquaculture systems (Ali *et al*., 2016; Shoko *et al*., 2016). In this research, the production costs in each combination showed a logical trend, where more species lead to higher total production costs due to the additional expenses from seeds and feed. Nonetheless, further results showed that the increase in production costs was offset by higher total production.

The input-output configuration in each species combination shows greater efficiency as seen from higher increase of output percentage (production) than the increase in input (cost). This is further confirmed by the BCR value for all species combinations (ranging from 1.03 to 1.61), which is greater than 1, indicating a profitable business (Ali *et al*., 2018). Other research have also shown that IMTA cultivation systems show higher economic efficiency compared to monoculture and polyculture systems. Biswas *et al*. (2019) reported a higher BCR value in the IMTA system (2.64) compared to the polyculture system (2.03). Similarly, Jewel *et al*. (2021) found BCR values of 1.26, 1.96, and 2.49 for monoculture, polyculture, and IMTA systems, respectively, further supporting the economic efficiency of IMTA.

The growth of paddy was not specifically calculated, but it showed similar trends as the growth of other species. Therefore, it was assumed that the BCR value would not change significantly if paddy was included in the costs and income. In conclusion, increasing the species combination in the IMTA-Paddy system of milkfish culture can lead to higher profits and greater economic efficiency.

Water quality parameters

Water quality is a crucial factor in aquaculture that affects production (Wang *et al*., 2020; Zhang *et al*., 2019). The temperature and salinity in each tank remained relatively stable at 25 to 32°C and 15 to 35 ppt, respectively (Yap *et al*., 2007). These values can be tolerated by eurythermal and euryhaline milkfish (Bagarinao, 1991; Juario *et al.*, 1984). The presence of floating rice plants also helps maintain suitable temperature by providing shade and protection from sunlight.

The dissolved oxygen levels in each tank of the species combination are ideal for milkfish, ranging from 6.2 to 6.3 mg L^{-1}. The optimal dissolved oxygen level for organisms in brackish waters, including milkfish is above 5 mg L^{-1} (Pantjara *et al.*, 2015). The aeration system used in this study is known to have contributed to the high dissolved oxygen concentration (Kumar *et al.*, 2013). The presence of paddy may also improve the diffusion of oxygen from the atmosphere into the water through the leaves to the roots (Li *et al.*, 2019). Furthermore, the fluttering of paddy leaves by the wind encourages the diffusion of oxygen on the water's surface (Foster-Martinez & Variano, 2016).

The pH level remained relatively stable during maintenance, with slight fluctuations from 6.8 to 6.9 within the suitable range for milkfish (6.5 to 8.5) (Yap *et al.*, 2007). The low pH observed in this research could be attributed to the utilization of organic waste by tiger prawns and shellfish (Eldani & Primavera, 1981; Yap *et al.*, 2009; Zakri & Mohamed, 2020). The presence of organic acids in paddy roots, which may inhibit the production of unionized ammonia in water (Li *et al.*, 2019) could be associated with the low pH observed in this study.

Ammonia (NH_3) levels during rearing ranged between 0.0177 to 0.0557 mg L^{-1} below the harmful threshold (above 1 mg L^{-1}) (Lawson, 1995). As the indicator of feed waste, feces, and excretion products (Dauda *et al.*, 2019; Nederlof *et al.*, 2021), lower NH_3 levels were observed with increasing species diversity. This can be attributed to the presence of tiger prawns and mussels that utilize leftover feed, feces, and excretions as food (Simao *et al.*, 2013; Zakri & Mohamed, 2020). Paddy with the floating method may directly absorb inorganic N through its roots (Feng *et al.*, 2016; Srivastava *et al.*, 2017). Li *et al.* (2019) reported that paddy significantly reduced NH_3 by 25.4 to 27.0% in ponds. Similarly, Feng *et al.* (2016) showed that NH_3 in fish and paddy polycultures are 60.27% lower than in fish monocultures.

CONCLUSION

This research demonstrates that integrating milkfish, tiger prawns, mussels, and rice in a brackish water IMTA-Paddy system yields the highest growth performance and economic value. This species combination proved to be the most compatible, complementary, and profitable. Future research will focus on scaling up to commercial cultivation to assess productivity, ecological impacts, and potential profitability in real-world conditions. This represents a critical step toward advancing the potential of integrated multi-trophic aquaculture (IMTA) with paddy in brackish water systems.

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