Omni-Akuatika, 22 (1): 1 - 13, 2026
ISSN: 1858-3873 print / 2476-9347 online

Research Article

journal homepage: http://ojs.omniakuatika.net

Assessment of Integrated Agriculture–Aquaculture Scenarios for Aquatic Animal Cultivation and Floating Rice in Coastal Zones to Optimize Productivity and Nutrient Recovery

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Received 18 January 2026; Revised 27 April 2026, Accepted 13 May 2026;
Available online 2 July 2026, Published 2 July 2026

ABSTRACT

This study represents a potentially groundbreaking exploration into the dual integration of agriculture and aquaculture (IAA) systems in brackish water. The objective of this work was to assess the production performance of the IAA system under various species combination scenarios, which are pivotal in multi-species cultivation. Conducted over an 80-day period, this study employed three species combination scenarios: milkfish and rice (Scenario 1), milkfish, tiger shrimp, and rice (Scenario 2), and milkfish, tiger shrimp, mussel, and rice (Scenario 3). A floating-bed system was utilized for rice cultivation in all scenarios. The pilot scale experiment was meticulously designed, including tarpaulin ponds, acclimatization, feed, and aeration to establish a conducive environment within the system. Results revealed proportional species growth, with the mortality rate (MR) of milkfish, tiger shrimp, and rice showing no significant impact ($P > 0.05$) from species combinations. However, significant differences ($P < 0.05$) were observed in the weight gain (WG) and specific growth rate (SGR) of milkfish, as well as the height gain (HG) of rice among species combinations. Nutrient removal efficiency (NRE) for nitrogen and phosphorus increased significantly with the combined number of species. Species combinations also had a significant effect on feed efficiency ratio (FER). All observed parameters in scenario 3 (IAA) demonstrated superiority, making it a more practical approach for the IAA model in coastal zones. This study validates an optimal species combination model, providing a scalable framework to advance productivity and nutrient efficiency in future integrated coastal aquaculture systems.

Keywords: brackish water, Integrated Agriculture-Aquaculture (IAA), production performances, species combination

ABSTRAK

Studi ini mewakili potensi eksplorasi terobosan dalam integrasi ganda pertanian dan budidaya perairan (IAA) di air payau. Tujuannya adalah menilai kinerja produksi sistem IAA dalam berbagai skenario kombinasi spesies, yang penting dalam budidaya multi-spesies. Penelitian yang dilakukan selama 80 hari ini menggunakan tiga skenario kombinasi spesies: bandeng dan padi (Skenario 1), bandeng, udang windu, dan padi (Skenario 2), serta bandeng, udang windu, remis, dan padi (Skenario 3). Sistem hamparan terapung digunakan untuk penanaman padi di semua skenario. Percobaan skala percontohan dirancang dengan cermat, termasuk kolam terpal, aklimatisasi, pakan, dan aerasi untuk menciptakan lingkungan yang kondusif dalam sistem. Hasil penelitian menunjukkan pertumbuhan spesies proporsional, dengan angka kematian (MR) bandeng, udang windu, dan padi tidak menunjukkan dampak signifikan ($P > 0,05$) dari kombinasi spesies. Namun, perbedaan yang signifikan ($P <0,05$) diamati pada pertambahan berat badan (BB) dan laju pertumbuhan spesifik (SGR) ikan bandeng, serta pertambahan tinggi badan (HG) padi antar kombinasi spesies. Efisiensi penghilangan unsur hara (NRE) untuk nitrogen dan fosfor meningkat secara signifikan seiring dengan bertambahnya jumlah spesies. Kombinasi spesies juga mempunyai pengaruh yang signifikan terhadap rasio efisiensi

http://dx.doi.org/10.20884/1.oa.2026.22.1.1329

pakan (FER). Semua parameter yang diamati dalam Skenario 3 (IAA) menunjukkan keunggulan, sehingga menjadikannya pendekatan yang lebih praktis untuk model IAA di wilayah pesisir. Studi ini memvalidasi model kombinasi spesies optimal, menyediakan kerangka kerja yang dapat diskalakan untuk meningkatkan produktivitas dan efisiensi nutrisi dalam sistem akuakultur pesisir terpadu di masa mendatang.

Kata kunci: air payau, pertanian-akuakultur terpadu (IAA), kinerja produksi, kombinasi spesies

1. Introduction

Aquaculture in brackish waters plays a crucial role as a food production systems and source of livelihoods of communities in coastal zones (Mondal et al., 2021). Approximately 27% of the world's population resides in these areas, categorized as near-coastal zones (Reimann et al., 2023). In Indonesia, 60% of the population inhabits coastal zones, with a population density of 80 individuals per square kilometer, which is twice the global population density (Kantamaneni et al., 2022; Khairulbahri, 2022). The predominant livelihood for residents is aquaculture in ponds, such as cultivating tiger prawn, whiteleg shrimp, milkfish, and seaweed (MMAF, 2023). Approximately 80% of these cultivation systems are managed using traditional methods (Tarunamulia and Sammut, 2023). While these traditional systems exhibit low productivity, it is supported by the historical experience of farmers and their production of organic food materials (Jumiati et al., 2023). Additionally, spatially Indonesia possesses an estimated 2.96 million hectares of area suitable for brackish water aquaculture, with only approximately 22.7% currently utilized (MMAF, 2023). These advantages can make a positive contribution to the social and economic systems in coastal regions. However, the vulnerability of these zones to climate change necessitates an appropriate approach for adaptation and mitigation to ensure aquaculture sustainability.

Integrated agriculture-aquaculture (IAA) is a cultivation system that simultaneously combines the agricultural and fisheries sectors, aiming to enhance diversification, intensification, efficiency of natural resources, and productivity (Huong et al., 2018; Ignowski et al., 2023). The IAA is widely practiced through three main types of integration: crop-fish, livestock-fish, and crop-livestock-fish (Awuor et al., 2023). This system is considered superior to monoculture systems which have low potential for adaptation to competition and the impact of waste which threatens the sustainability of production (Amoussou et al., 2022; Thomas et al., 2021). Additionally, IAA stands out as one of the most effective strategies for enhancing small-scale cultivation productivity (Hasimuna et al., 2023) through the maximum utilization of all resources, such as land, water and feed, and at the same time minimizing waste (Popp et al., 2018). Therefore, IAA promotes environmentally friendly practices, sustainability, and food security (Ibrahim, et al., 2023a), making it an option for climate change adaptive and mitigation strategies (Maulu et al., 2021; Orsag et al., 2023).

In the realm of aquaculture, the system of integrated rice-fish (IRF), known as *Minapadi* in Indonesia, represents a widely recognized practice of IAA to date. Across Asian nations, the historical implementation of the IRF system in freshwater environments has spanned over 2000 years, demonstrating its efficacy in enhancing productivity and ecosystem health (Inayat et al., 2023) . The strategic value of integrating aquatic animals with rice cultivation is underscored by the pivotal role of rice as a staple food for approximately half of the global population, thus rendering this agricultural crop a primary contributor to food security (Ibrahim, et al., 2023b; Yassi et al., 2023). Various freshwater species that have been integrated with rice include common carp (*Cyprinus carpio* Linnaeus), tilapia (*Oreochromis niloticus* Linnaeus), catfish (*Clarias batrachus* Linnaeus), silver barb (*Barbonymus gonionotus* Bleeker), crayfish (*Cherax quadricarinatus* von Martens), giant fresh water prawn (*Macrobrachium rosenbergii* De Man), and others (Ibrahim, et al., 2023b). Recent reports indicate the implementation of IAA in brackish water ponds, although within limited scope. For instance, in India, rice (*Oryza sativa* Linnaeus) has been integrated with whiteleg shrimp (*Litopenaeus vannamei* Boone) (Goswami and Ghosal, 2022) and giant tiger prawn (*Penaeus monodon* Fabricius) in Indonesia (Hendrajat et al., 2020; Sahabuddin et al., 2024). Integration of rice with several species, such as tilapia (*O. niloticus* L.), giant tiger prawn (*P. monodon* F.), blood cockles (*Tegillarca granosa* Linnaeus.), and sandfish (*Holothuria scabra* Jaeger) through the integrated multi-trophic aquaculture (IMTA) system on a laboratory scale, has also been reported by Heriansah et al. (2023), Alifia et al. (2023), and Kabangnga et al. (2023). These studies underscore the need for much study to develop and expand such systems in brackish water environments integrating local knowledge and simple technology.

In the present study, we integrated milkfish (*Chanos chanos* Fabricius), giant tiger prawn (*P. monodon* F.), and mussel (*Glauconome* *virens* Linnaeus) with floating bed of rice (*O. sativa* L.) in brackish water. Apart from being economically valuable and locally available, these species have different trophic levels. Floating bed and multi-trophic system represents conceptual and practical approaches to climate change adaptation and mitigation (Goda et al., 2024; Maulu et al., 2021). An essential consideration in multi-trophic aquaculture operations is the combination of species, as it determines harmonious species interactions and optimal utilization of trophic and spatial niches in the system (Arriesgado et al., 2022; Mondal et al., 2021; Thomas et al., 2021). This study may mark the first exploration of dual integration through the IAA system in brackish water. The objective of this research was to assess the production performance of the IAA system under different species combination scenarios. These findings are valuable for expanding insight to exploring the potential and best practices of IAA to promote sustainable brackish water cultivation in coastal zones.

2. Materials and methods

2.1 Study Site and Integrated Culture System

The research was conducted in one of the traditional community ponds in the Lanrisang Districk, Pinrang Regency area (**Figure 1**), the largest pond area in South Sulawesi, Indonesia. On the pond land, nine tarpaulin ponds with dimensions of 2 × 2 × 1 m (total volume of 4,000 L, containing 3,200 L of water) were constructed and used as pilot scale experimental units. The experimental units were maintained as a closed system with no water exchange throughout the 80-day study period. Meanwhile, nine floating beds made of bamboo, measuring 1 × 1 m and equipped with fine-mesh netting and palm fiber, were prepared as the rice planting place.

2.2 Species Preparation and Acclimatization

Milkfish and giant tiger prawn juveniles were commercially obtained from local hatchery units, mussel were collected from the nearest river estuary to the research location, and salt-tolerant rice seeds (varieties Inpari) were obtained from seed providers in Maros, South Sulawesi. Three stocks of aquatic animal species, namely milkfish (300 individuals), giant tiger prawn (200 individuals), and mussel (100 individuals), were gradually acclimatized over a period of 3 days. Meanwhile, rice plants (300 clump) were sown at the experimental site up to a specific height. Prior to the stocking of these species, each experimental unit was supplied with 280 L of brackish water (with an mean salinity of 15 ppt), fertilized (0.1 kg of urea and triple superphosphate, respectively), and liquid probiotics (20 mL). Subsequently, experimental units were left without intervention for 7 days to promote initial natural food within the system.

Figure 1. Map of experimental location (mapped using QGIS 3.16.6-1 software)

2.3 Experimental Design and Stocking Density

In the present study, three groups of species combination scenario, namely Scenario 1 (Sc.1 = milkfish and rice), Scenario 2 (Sc.2 = = milkfish, giant tiger prawn, and rice), and Scenario 3 (Sc.3 = milk fish, giant tiger prawn, mussel, and rice) (**Figure 2**). These three scenarios were employed as treatment units and tested in triplicate to evaluate the best scenario for IAA in brackish water. A total of 30 milkfish (12.3 ± 0.1 g individuals^{-1}), 30 giant tiger prawn (12.3 ± 0.1 g individuals^{-1}), and 30 mussels (30.1 ± 0.2 g individuals^{-1}) were each randomly distributed for each experimental unit. Additionally, a total of 30 rice clump (height of 17.8 ± 0.1 cm clump^{-1}) were also randomly moved to each floating bed and subsequently floated onto the experimental units. These stocking densities reflect the traditional aquaculture practices customary to the study location.

2.4 Feeding and Rearing Management

Over the 80-day rearing period, the milkfish were fed commercial feed (21% crude protein and 8% fat) three times a day (at 06:00, 12:00, and 18:00 local times) at a feeding rate of 5% of the biomass Arriesgado et al. (2022). Moreover, the milkfish were weighed (digital scales Camry EHA401) at 10-day intervals to adjust the subsequent feeding amounts. Continuously aeration was provided to each experimental unit using a Resun LP-100 blower to ensure a steady supply of dissolved oxygen.

The water quality parameters of each experimental unit, including salinity, pH, dissolved oxygen, and temperature, were monitored daily using the refractometer salinity (RHS 10 ATC), pH meter (Lustron PH-201), and DO meter (Lutron DO-5509). Measurements for total total nitrogen (TN) and total phosphorus (TP) parameters were taken at the beginning, middle, and end of the experiment. The concentrations of these two parameters were determined from 500 mL of water in polypropylene (PP) sample bottles in the laboratory, following the standard guidelines of the American Public Health Association (APHA, 2017).

2.5 Biometric Measurements and Performance Evaluation

The body weight of each aquatic animal was recorded from 15 individual samples at 10-day intervals (Hardanu et al., 2025).. For rice plants, growth performance was assessed based on plant height, measured from the soil surface (base of the stem) to the tip of the longest panicle (Sahabuddin et al., 2024), likewise using 15 clumps at 10 day intervals. Recording of dead species was carried out daily during the experiment. Furthermore, at the end of the experiment several biometric performances were evaluated, including the mortality rate (MR) (Piech et al., 2023), weight gain (WG), specific growth rate (SGR), and nutrient removal efficiency (NRE) (Pham & Bui, 2020). Additionally, feed efficiency ratio (FER) is assessed using the equation proposed by Khater et al. (2023). Each performance is calculated using the respective equations:

$$\text{MR (\%)} = 100 \times (Ni - Nf) / Ni$$

$$\text{WG (g)} = Wf - Wi$$

$$\text{HG (cm)} = Hf - Hi$$

$$\text{SGR (\% day}^{-1}) = 100 \times (\text{Ln } Wf - \text{Ln } Wi) / t$$

$$\text{NRE (\%)} = 100 \times (Ci - Cf) / Ci$$

$$\text{FER} = (WG \times nt) / FI$$

In the given equation, Ni and Nf denotes the number of fish/prawn/mussel/rice in the initial and the final of experiment, respectively. Wi signifies the initial weight (g) and Wf is the final weight (g). Hi and Hf denotes the initial and final height of the rice plant, respectively. Futhermore, Ci represent the initial concentrations and Cf is final concentrations nutrient compounds. Meanwhile, FI symbol in FER calculations is the feed intake (g) during the rearing time. It is important to note that the initial concentration for the NRE calculation was set according to the measurements taken in the middle of the experiment.

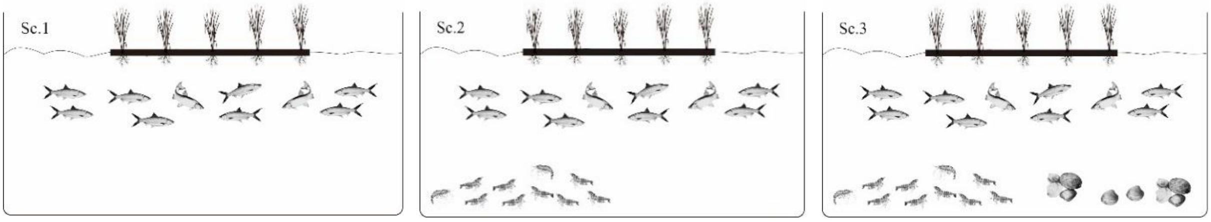

Figure 2. Illustration of three scenarios (Sc.) of species combinations in the IAA system

2.6 Statistical Analysis

The data are presented as mean ± standard deviation (SD) (n = 3). After undergoing the Shapiro-Wilk and Levene tests ($P > 0.05$), confirming adherence to parametric statistical assumptions, one-way analysis of variance (ANOVA) was employed to evaluate the performance among different species combination scenario. Subsequently, Duncan Multiple Range Test (DMRT) were conducted at the 95% significance level ($P < 0.05$). In addition, the Independent-Samples T Test was used to determine significant differences for the performance of species that were only involved in two scenarios. All statistical analyses were performed using SPSS for Windows v.25.0 software (SPSS Inc., Chicago, IL, USA). The data display in graphical form was processed using Microsoft Excel 2019 v.2401 software.

3. Results and Discussion

3.1. Results

The results of the observation of water quality parameters, nutrient removal efficiency (NRE), and feed efficiency ratio (FER) are presented in **Table 1**. The recorded values for the four general water quality parameters in each species combination scenario were observed not to show extreme variations during maintenance, and were not significantly different between the species combination scenarios. The percentage of NRE for total nitrogen (TN) and total phosphorus (TP) was significantly influenced ($P < 0.05$) by the species combination scenarios. The findings indicate a significant ($P < 0.05$) increase in NRE for TN and TP as the number of combined species increased. For the assessment of FER, it is imperative to note initially that the WG values of all aquatic animals is incorporated into the calculations. Considerations include not only milkfish, which is a species intentionally fed within the system, but also tiger shrimp and mussel, which utilize the feed in the form of leftover feed and feces (metabolic products of consumed feed). The results reveal that the cumulative FER is significantly influenced by the scenarios involving species combinations, as evidenced by a significantly difference ($P < 0.05$). The FER in Scenario 3 was significantly ($P < 0.05$) higher than that in Scenario 1 and Scenario 2. However, the FER of Scenario 1 was comparable to that of Scenario 2 ($P > 0.05$).

Figure 3 illustrates the average weights of milkfish, giant tiger prawn, and mussel, as well as the height of rice, recorded every 10 days over an 80-day cultivation period, in each species combination scenario. Overall, all IAA aquaculture model scenarios performed well, as all species in each model exhibited weight gain over the course of the maintenance period. However, the milkfish, tiger prawn and rice species in scenario 3 grew at a faster rate compared to scenario 1 and scenario 2. For mussels, due to their involvement in only one scenario, it becomes challenging to judge which scenario is superior, presenting a limitation in this study.

Low mortality rate (MR) and high growth (WG and SGR) are always desirable outcomes in any aquaculture system. The recapitulation of observed values for MR, WG, and SGR for aquatic animals is presented in **Table 2**.

Table 1. The water quality parameter values, nutrient removal efficiency (NRE), and feed efficiency ratio (FER) in scenarios different species combinations. Values in rows followed by different letters indicate statistically significant differences ($P < 0.05$)

Parameters	Skenario (Sc.) groups		
	Sc.1	Sc.2	Sc.3
Water quality			
Salinity (ppt)	12.3 ± 1.6 ^{a}	12.4 ± 1.3 ^{a}	12.4 ± 1.6 ^{a}
pH	6.9 ± 0.2 ^{a}	6.8 ± 0.2 ^{a}	6.9 ± 0.2 ^{a}
Dissolved oxygen (mg L^{-1})	6.2 ± 0.4 ^{a}	6.1 ± 0.4 ^{a}	6.3 ± 0.4 ^{a}
Temperature (ºC)	28.2 ± 1.4 ^{a}	28.3 ± 1.3 ^{a}	28.2 ± 1.3 ^{a}
Nutrient removal efficiency (NRE, %)			
NRE of TN	29.8 ± 2.4^a	40.3 ± 2.8^b	68.5 ± 1.1^c
NRE of TP	21.7 ± 3.0^a	29.5 ± 3.5^b	44.5 ± 2.0^c
Feed efficiency ratio (FER)	0.45 ± 0.01^a	0.46 ± 0.01^a	0.57 ± 0.01^b

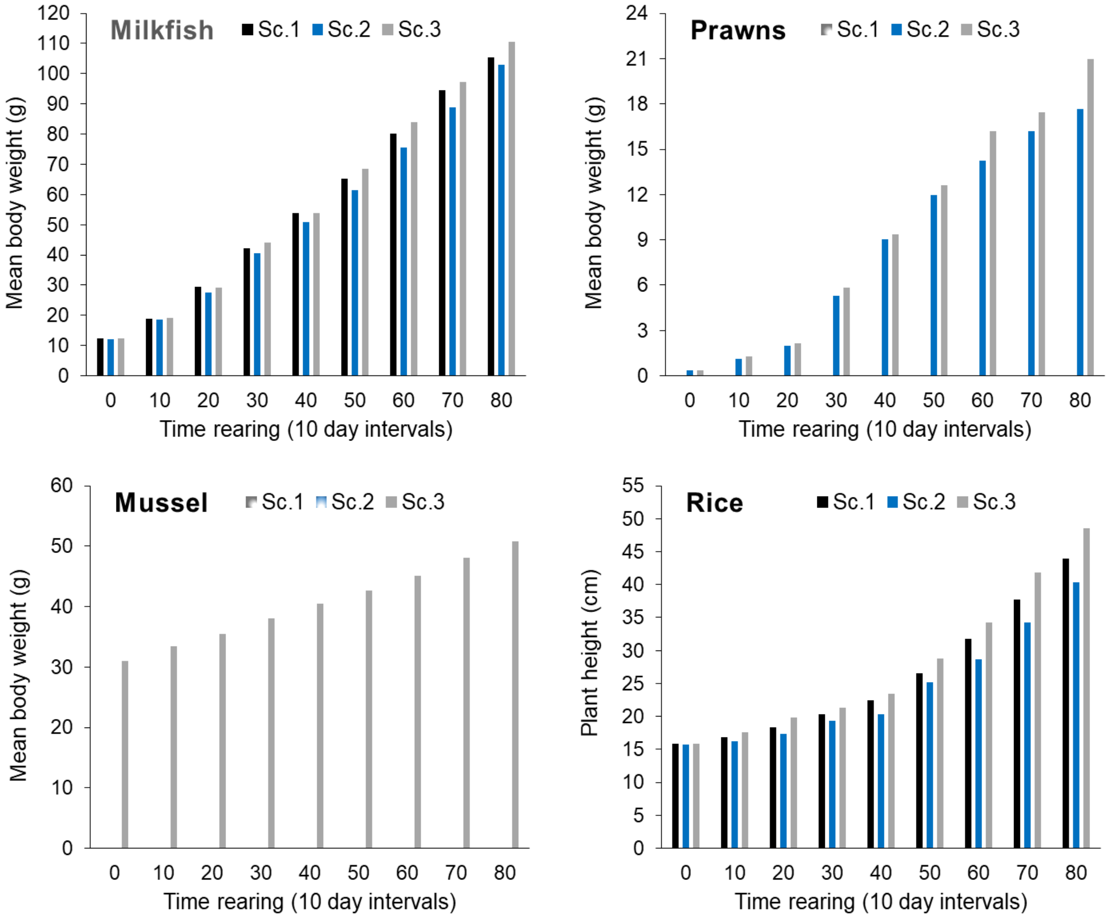

Figure 3. The enhancement of the average weight of each cultivated species in the scenario (Sc.) involving combinations of different species

Table 2. The mortality rate (MR), weight gain (WG), and specific growth rate (SGR) of aquatic animals values in scenarios different species combinations. Values in columns followed by different letters indicate significant differences ($P < 0.05$)

Species	Scenario (Sc.) groups	MR (%)	WG (g)	SGR (% days^{-1})
Milkfish	Sc.1	1.1 ± 1.9^{a}	93.1 ± 0.4^{a}	2.69 ± 0.01^{a}
	Sc.2	4.5 ± 2.0^{a}	90.6 ± 0.3^{b}	2.66 ± 0.02^{b}
	Sc.3	2.2 ± 1.9^{a}	98.2 ± 0.4^{c}	2.74 ± 0.01^{c}
Giant tiger prawn	Sc.1	-	-	-
	Sc.2	13.3 ± 5.7^{a}	17.3 ± 0.4^{a}	4.7 ± 0.13^{a}
	Sc.3	11.1 ± 1.9^{a}	20.1 ± 0.8^{b}	5.1 ± 0.11^{b}
Mussel	Sc.1	-	-	-
	Sc.2	-	-	-
	Sc.3	14.4 ± 5.1	19.8 ± 0.7	0.62 ± 0.01

Following an 80-day experimental period, MR for milkfish and tiger shrimp were observed to be less than 15%, and notably, not significantly influenced ($P > 0.05$) by the species combination scenarios. However, the growth rates (WG and SGR) of milkfish and giant tiger prawn in Scenario3 were significantly higher ($P < 0.05$) compared to Scenario1 and Scenario 2.

Furthermore, significant differences were observed between Scenario1 and Scenario2 ($P < 0.05$). Mussels in this study are challenging to compare as they were only involved in one specific combination scenario.

Table 3 presents the mortality rate (MR), height gain (HG), and specific growth rate (SGR) of rice plants, demonstrating patterns analogous to the biometric performance of aquatic animals (Table 2). The species combinations in different scenarios did not have a significant impact on the MR of rice plants ($P > 0.05$). However, the scenarios significantly influenced both WG and SGR ($P < 0.05$). The highest WG and SGR were observed in Scenario 3, followed by Scenario 2 and Scenario 1, and these differences were found to be statistically significant ($P < 0.05$) among the three scenarios.

3.2. Discussion

Although there have been advancements in addressing global food security vulnerabilities, sustained efforts remain crucial given rapid population growth and the looming threat of climate change, necessitating appropriate adaptation and mitigation strategies (FAO, 2022; Orsag et al., 2023). In aquaculture, the diversification of ventures stands out as a key element for successful adaptation, while environmentally friendly production practices serve as a form of mitigation against the impacts of climate change (Maulu et al., 2021). This study endeavors to incorporate both strategic points through breakthroughs in the dual integration of agriculture and aquaculture (IAA) by combining integrated multi-trophic aquaculture (IMTA) and integrated rice-fish (IRF) systems, termed IMTA-IRF. In multi-species systems, such as the one in this study, information on water quality and biometrics, including mortality, growth, nutrient reduction, and feed efficiency, becomes paramount.

Water quality plays a crucial role in influencing production performance within aquaculture systems. This study examines four common water quality parameters—salinity, pH, dissolved oxygen, and temperature, all falling within ranges tolerable for aquatic organisms. Milkfish, a euryhaline and eurythermal species, exhibits optimal growth at salinities and temperatures ranging from 0.5 to 40 ppt and 25 to 32°C, with a pH of 6.5 to 8.5 (Yap et al., 2007). The Indonesian National Standard (SNI) recommends a salinity of 5 to 35 ppt, a temperature between 28 and 32°C, and a pH level between 7.0 and 8.5 for milkfish. Giant tiger prawn thrive optimally at salinities of 15 to 25 ppt, temperatures of 25 to 28°C, and pH levels of 7.5 to 8.5, tolerating pH values as low as 6 (Aftabuddin et al., 2018). (Aftabuddin et al., 2018).

The Indonesian National Standard (SNI) recommends a salinity of 10 to 40 ppt, a temperature between 28 and 30°C, and a pH level between 7.5 and 8.5 for tiger shrimp. The mussel *G. virens* (L) lacks specific references for optimal water quality parameters. However, the brackish water mussel, *Mytilopsis leucophaeata* C., can grow within salinity and temperature ranges of 0 to 25 ppt and 10 to 50°C, respectively (Verween et al., 2007). Recommended values for dissolved oxygen (DO) in intensive aquaculture are higher than 5.0 mg L^{-1} (Mondal et al., 2020). Throughout the experiment, average DO levels never fell below 6 mg L^{-1}. In addition to continuously supplied aeration systems, the photosynthetic capability of rice contributed to relatively high DO levels (Srivastava et al., 2017). Meanwhile, salinity appears to be a sensitive parameter for rice plants, despite the use of salt-tolerant varieties. Clear symptoms, such as yellowing leaves, were observed, similar to those reported by Ichsan et al. (2022). However, no significant differences were observed for all water quality parameters in all experimental ponds (Table 1). This condition emphasizes that the variation in experimental results was not attributed to water quality parameters but rather to the influence of the combination of different species.

Table 3. The mortality rate (MR), plant height gain (HG), and specific growth rate (SGR) of rice plants values in scenarios different species combinations. Values in columns followed by different letters indicate significant differences ($P < 0.05$)

Species	Scenario (Sc.) groups	MR (%)	HG (cm)	SGR (% $days^{-1}$)
Rice	Sc.1	17.8 ± 3.8^{a}	28.3 ± 0.5^{a}	1.27 ± 0.01^{a}
	Sc.2	20.0 ± 3.3^{a}	24.9 ± 0.4^{b}	1.19 ± 0.02^{b}
	Sc.3	14.4 ± 1.9^{a}	32.8 ± 0.5^{c}	1.40 ± 0.06^{c}

Regardless of the absolute value, each species in the three simulated IAA cultivation models shows an increasing trend in weight at each 10-day interval (Figure 2), similar to several related studies reported previously (Amalia et al., 2022; Li et al., 2021). It is noteworthy that artificial feed serves as the primary energy source in this study, generating derivative nutrient sources in the form of leftover feed and feces from each species (organic matter), as well as the excretions of each species and the decomposition products of leftover feed and feces (inorganic matter) (Dauda et al., 2019). Furthermore, during pond preparation, researchers observed the cultivation of lab-lab (phytoplankton) as natural food (Anand et al., 2018). The net energy supplied from artificial feed (21% protein and 8% fat, feeding rate 5%, three times a day) and its derivatives, as well as natural feed, seemingly exceeds the basal metabolism and voluntary activity energy needs of each species. Thus, there remains energy for the growth of milkfish, tiger shrimp, mussel, and rice. This concept of energy budgeting (Weidner et al., 2020) may help explain the observed weight increase in each species and combination scenario.

As expected, the mortality rate (MR) in this study remained consistently low for all species (not exceeding 20%) and was unaffected by any scenario (Table 2 and Table 3). The occurrence of deaths was limited to the first week after stocking, potentially indicating an initial response to inhabiting a new habitat alongside several cohabiting species. Despite the increased trophic complexity in Scenario 3, the observed mortality remained comparable to other scenarios, suggesting that the integrated system effectively maintained environmental stability and mitigated potential competition or stress among the cohabiting species. In various aquaculture systems, the MR of milkfish and tiger shrimp has been evaluated, with better outcomes found in this study. For instance, Arriesgado et al. (2022), utilizing an IMTA system, reported MR of 9.8% for milkfish and 55.9% for tiger shrimp, co-cultured with red algae (*Gracillaria verrucosa* H.) and horse mussels (*Modiolus modulaides* R.) for 90 days in ponds at a salinity of 25 ppt. The mortality rate of horse mussels in that study was notably high, although the specific value was not provided. Amalia et al. (2022) documented a tiger shrimp MR of 10.0% in an IMTA system with red algae (*G. verrucosa* H.) and blood cockles (*Anadara granosa* L.) at a salinity of 21 ppt for 4 weeks in fiberglass tanks, significantly lower than the monoculture system with an MR value of 13.7%. Sahabuddin et al. (2024) recorded a tiger shrimp MR of 79.2 and 79.8% when polycultured with rice for 65 days at a salinity of 7 ppt. It remains challenging to compare with other studies due to the absence of publications related to rice mortality rates in integrated systems in brackish water. Differences in experimental methods may contribute to the variation in MR among studies, including the results of this study. The consistency in survival rates across our treatments implies that the managed integrated environment was sufficient to support all species regardless of the model complexity.

Aquatic animals and rice plants exhibit significant variation in biometric growth parameters (WG and SGR) across different combination scenarios, as detailed in Table 2 and Table 3. Absolute values of WG and SGR for each species varied in comparison to prior studies, possibly due to distinct system designs. However, integrated systems consistently demonstrated more uniform growth patterns based on cultivation systems. In a study by Amalia et al. (2022), giant tiger prawn exhibited significantly higher SGR (5.8% day^{-1}) within an IMTA system compared to monoculture systems (5.6% day^{-1}). Alifia et al. (2023) investigation involving a broader combination of species (tilapia, giant tiger prawn, blood cockle, sandfish, and rice) revealed higher SGR for giant tiger prawn co-cultivated with all species (IAA) (3.3% day^{-1}). This was significantly greater than IMTA (2.9% day^{-1}), polyculture (3.0% day^{-1}), and monoculture systems (2.6% day^{-1}), aligning with the current study findings. Our experiments underscore the role of cockles and rice in enhancing the biometric performance of others species in the system. Integrated studies on *G. virens* (L) cockles are currently lacking. However, a recent study, found that the SGR of blood cockles in the IMTA-rice system (0.14% day^{-1}) was higher than IMTA-non-rice (0.10% day^{-1}), polyculture (0.07% per day^{-1}), and monoculture systems (0.09% day^{-1}) (Kabangnga et al., 2023), a similar trend to the findings in this study. The better growth observed in these complex models occurs because of the cooperative relationship between the different organisms in the pond. The rice plants and cockles act as natural filters that turn waste into additional food sources for the fish and shrimp. Because the environment is cleaner and more food is available, the animals do not need to spend as much energy adjusting to their surroundings, allowing them to grow faster. In short, these results show that growing various types of organisms together creates conditions that help everything thrive more effectively. The impact of species combinations within the system can elucidate these findings, particularly regarding coexistence and positive interactions among species based on their trophic levels (Arriesgado et al., 2022; Heriansah et al., 2022a).

Sahabuddin et al. (2024) specifically reported higher performance in HG rice plants when polycultured with giant tiger shrimp in brackish water (salinity 7 ppt) compared to the findings of the current study. Although the HG plants demonstrated survival with a relatively low mortality rate (Table 3), the relatively high salinity factor (average value of 12.4 ppt) in this study likely contributed to their HG performance of rice. Brackish water, known for causing salt stress, is a significant constraint for rice cultivation (Ichsan et al., 2022; Li et al., 2021). During exposure to salt stress, soluble carbohydrates play a crucial role in osmoregulation in rice (Kaur and Pati, 2017). Compounds essential for osmoregulation are presumed to be present in the excretions from milkfish, giant tiger shrimp, mussel, and decomposition products of residual feed and feces, making them available for rice absorption. The floating-bed method maximizes the absorption of these compounds by rice roots (Srivastava et al., 2017). However, the energy absorbed from these nutrients seems to be primarily allocated to meet nutritional demands for overcoming salt stress through osmotic adjustment (Tian et al., 2016), possibly explaining the observed low height increment of rice plants in all species combination scenarios.

The influence of feed on three crucial aspects in aquaculture: growth (biological aspect), waste impact (ecological aspect), and production costs (economic aspect) has consistently garnered attention (Heriansah et al., 2022b). Therefore, NRE performance (about feed N and P nutrients are utilized for growth) and FER performance (about feed is converted to body weight) were assessed in this study. Similar studies evaluating both aspects are lacking to date, making it challenging to determine whether the NRE and FER in this study are superior or not. However, conceptually, each species role based on its trophic level can elucidate NRE and FER performance in each species combination scenario.

In addition to milkfish as a fed species consuming feed, giant tiger shrimp facilitates the nutrient utilization pathway in this study, acting as a benthic feeder capable of consuming sinking feed residues (Simão et al., 2013). Furthermore, this species can feed on the feces of milkfish and mussels (Eldani and Primavera, 1981). Another pathway is contributed by the filter-feeding mussel *G. virens* (L) (Zakri and Mohamed, 2020). Through filtration mechanisms, this species can absorb suspended organic and inorganic waste at the water bottom (Zhang et al., 2019). Finally, rice plants, employed using floating-bed methods, serve as a nutrient utilization pathway through the absorption of inorganic nutrients (Li et al., 2021). The floating beds, measuring 1 m^2, utilized in this study, occupy more than 10% of the water surface, as recommended by (Henares and Camargo, 2014). Consequently, rice roots can effectively assimilate inorganic nutrients on the media surface, such as nitrogen (N) and phosphorus (P) (Li et al., 2021). This explanation ultimately provides a logical basis for the significantly higher percentages of NRE TN and TP, as well as FER, found in combinations involving multiple species with differing trophic levels (Scenario 3).

The findings of this study reveal intriguing aspects of the IAA model. Scenario 3 (IMTA-IFR), featuring a greater number of species, yields mortality rates comparable to those with fewer species (Scenarios 1 and 2), while not compromising other biometric performances. In fact, the growth performance, nutrient removal efficiency, and feed efficiency ratio in Scenario 3 surpass those in the other scenarios. The superiority of integrating aquatic animals and rice plants in the IMTA-IFR system stems from the trophic level benefits of each species (Thomas et al., 2021; Zhang et al., 2019). Milkfish (*C. chanos* F.) as a fed species, giant tiger shrimp (*P. monodon* F.) as a benthic feeder, mussel (G. *virens* L.) as a filter feeder, and rice (*O. sativa* L.) as an absorber of inorganic nutrients through a floating bed form a harmonious combination with high synergistic and low antagonistic relationships. These findings provide insights into the dual integration of IMTA and IFR systems in brackish water, which can promote environmentally friendly production diversification as an adaptive strategy and climate change threat mitigation (Maulu et al., 2021; Orsag et al., 2023).

4. Conclusion

This study demonstrates that the IAA system not only increases productivity and diversifies products but also ensures reliable nutrient waste removal and enhances feed efficiency. These outcomes align with recommendations for adaptive and mitigative strategies in response to climate change threats. The findings provide valuable insights into the potential of the IAA system as a beneficial aquaculture model, exploring best practices in IAA to promote sustainable brackish water aquaculture growth in coastal regions. However, it is imperative to conduct further experimental research to ensure the feasibility of implementing this system on a commercial scale. Additionally, there is a need to breed rice varieties tolerant to high salinity to support rice production in brackish water environments.

Acknowledgements

The authors extends gratitude to the farmers who participated in the series of research implementations. Special thanks are offered to the journal editor and anonymous reviewers of the Omni-Akuatika Journal for their excellent publication services. Additionally, the author expresses appreciation to Mr. Arpin Hardiana, a Master Program Student in the Fisheries Science program at Hasanuddin University, Indonesia, for his dedication in creating the base map of the research location.

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