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Evaluating Circular Bioeconomic Performance and Nutrient Recycling in Tarpaulin-Tank Hybrid Grouper Nursery under Integrated Multi-Trophic Aquaculture

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Abstract

Sustainable nursery systems are needed to improve resource-use efficiency, reduce organic waste accumulation, and enhance economic value in marine aquaculture. This study evaluated the bioeconomic performance and nutrient recycling capacity of integrated multi-trophic aquaculture (IMTA) for hybrid grouper (*Epinephelus fuscoguttatus* × *E. lanceolatus*) nursery culture in tarpaulin tanks within a circular bioeconomy framework. A 28-day experiment was conducted using four culture systems: hybrid grouper monoculture, hybrid grouper–sand sea cucumber–mussel, hybrid grouper–sand sea cucumber–seaweed, and hybrid grouper–sand sea cucumber–mussel–seaweed. The systems were operated without siphoning to promote internal waste reutilization. IMTA improved survival, feed utilization, solid waste reduction, and economic performance compared with monoculture. The hybrid grouper–sand sea cucumber–mussel treatment showed the best overall bioeconomic performance, with the highest survival rate (97.78%), lowest feed conversion ratio (3.51), highest feed efficiency (29.66%), and highest total revenue (USD 134.64). The hybrid grouper–sand sea cucumber–seaweed treatment achieved the greatest solid waste reduction relative to monoculture (54.15%). Extractive species generated additional co-product value, with waste-to-value conversion of 0.12–0.13 USD g⁻¹ waste and circularity ratios of 17.70–23.35%. These findings demonstrate that IMTA can partially transform hybrid grouper nursery culture from a linear production system into a more circular aquaculture model by reducing organic waste, recovering residual nutrients, and generating additional economic value from extractive organisms.

Keywords: circular aquaculture; hybrid grouper; nutrient recycling; tarpaulin tank; waste valorization; integrated multi-trophic aquaculture

1. Introduction

Grouper aquaculture is commonly organized as a sequential production system consisting of three main stages: hatchery, nursery, and grow-out. Among these phases, the nursery stage plays a critical role as an intermediate rearing phase that bridges the biological and managerial transition between hatchery and grow-out operations while determining the quality of juveniles entering the subsequent production stage (Amanda et al. 2020; Astari et al. 2023; Efendi et al. 2020; Firdausi and Mubarak 2021; Huang et al. 2023; Lei et al. 2022; Putra et al. 2025; Rochmad 2020; Safrita 2020). The biological performance of fish during the nursery phase strongly influences feed efficiency, survival rate, and production costs during the grow-out phase. Consequently, inefficiencies or failures occurring at this stage may significantly affect farm profitability and the overall sustainability of grouper aquaculture systems (Agustiyana et al. 2024; Apriani et al. 2024; Diatin, Arifianty and Farmayanti 2008; Diatin et al. 2021; Diatin, Effendi and Taufik 2020; Sumartin 2018).

In Southeast Asia, particularly in Indonesia, hybrid grouper (*Epinephelus fuscoguttatus* × *E. lanceolatus*) has emerged as one of the most economically valuable marine aquaculture commodities due to its high market demand in both domestic and international markets (Rimmer and Glamuzina 2019; Safrita 2020; Zhang et al. 2024). Despite substantial progress in hatchery technology, the nursery phase is still widely recognized as a major bottleneck within the grouper aquaculture value chain, especially for

small- and medium-scale aquaculture operations (Agustiyana et al. 2024; Astari et al. 2023; Efendi et al. 2020; Sabilu et al. 2021; Tomatala et al. 2018, 2021). High mortality rates, uneven growth, inefficient feed utilization, and the accumulation of uneaten feed and fecal waste are among the most common challenges reported in nursery systems.

These problems not only increase economic risks for farmers but also contribute to environmental pressure within aquaculture production systems. One of the primary challenges in nursery culture is closely associated with water quality management. Intensive feeding during the early juvenile stage rapidly generates a high organic waste load, which leads to the accumulation of organic matter, increased concentrations of dissolved nutrients, and fluctuations in key water quality parameters (DFO 2012; Fraga-Corral et al. 2022; Royan 2020; Turlybek et al. 2025; Verreth et al. 2023). These conditions are particularly evident in low-cost culture units such as concrete tanks and tarpaulin tanks, which are widely used by small-scale farmers in many aquaculture regions. Conventional management practices such as siphoning and large-volume water exchange can help reduce waste accumulation; however, these approaches often result in increased operational costs, higher labor requirements, and greater water consumption. Moreover, such practices typically follow a linear production paradigm characterized by input–production–waste disposal, which is considered inefficient from both economic and environmental sustainability perspectives. Therefore, more comprehensive approaches that emphasize resource-use efficiency and waste reutilization are increasingly needed in aquaculture management.

In recent years, aquaculture management strategies have gradually shifted toward sustainability-oriented approaches that emphasize resource efficiency, waste reduction, and value creation through the integration of biological processes within production systems. This concept is closely aligned with the circular bioeconomy framework, which views biological waste not merely as a by-product but as a potential resource that can be reutilized to improve the efficiency and productivity of aquaculture systems (Ahmad and Abdullah 2025; Arantzamendi et al. 2023; Hadley Kershaw et al. 2021; Masi et al. 2024; Verreth et al. 2023). Within this framework, Integrated Multi-Trophic Aquaculture (IMTA) has been proposed as a promising aquaculture management strategy that integrates organisms from different trophic levels, allowing nutrients released by fed species to be utilized by extractive organisms in co-culture systems (Azhar and Memiş 2023; Checa et al. 2024; Cotou et al. 2024; Goda et al. 2024; Lothmann and Sewilam 2023; Mihailov et al. 2025; Nissar et al. 2023; Papageorgiou et al. 2023; Ruiz-Vanoye et al. 2025; Yang et al. 2025).

From an ecological perspective, IMTA systems facilitate more efficient internal nutrient cycling and contribute to greater ecosystem stability within aquaculture environments (Chopin et al. 1995; Jumah Yashier Upling 2020; Ning et al. 2016; Royan 2020). In such systems, bivalves act as filter feeders that remove suspended organic particles from the water column, sea cucumbers consume organic detritus deposited on the culture bottom, while seaweeds assimilate dissolved inorganic nutrients such as nitrogen and phosphorus and contribute to the enhancement of dissolved oxygen levels (Kong et al. 2023; Neori et al. 2004, 2017; Ning et al. 2016; Putro et al. 2020). The complementary trophic roles of these organisms provide opportunities to improve water quality conditions, reduce environmental stress on cultured fish, and decrease reliance on intensive conventional management practices while simultaneously generating additional economic value through diversified production (Adrianto et al. 2005; Biswas et al. 2019; Budiardi et al. 2014; Chopin et al. 2012; European Commission 2020; Mihailov et al. 2025; Zamora et al. 2018). A number of studies conducted over the past decade have demonstrated that IMTA implementation can enhance feed utilization efficiency and nutrient retention (Checa et al. 2024; Chopin et al. 1995; Cutajar et al. 2022), improve fish growth performance and survival rates (Cotou et al. 2024; Heriansah et al. 2022; Stabili et al. 2019), and provide economic benefits through production diversification and increased total farm output (Nissar et al. 2023; Putra and Mulyono 2023; Shi et al. 2013). However, most of these studies have primarily focused on the grow-out phase and on large-scale aquaculture systems utilizing advanced technologies such as offshore floating cages and recirculating aquaculture systems (RAS). As a result, the applicability of these findings to nursery culture systems commonly practiced by small-scale aquaculture producers in tropical regions remains limited.

To date, empirical research examining the application of IMTA during the nursery phase as an intermediate rearing system for high-value marine finfish within a circular bioeconomy framework remains scarce. This limitation is particularly evident in hybrid grouper culture systems operated in low-cost rearing units such as tarpaulin tanks (Hannah et al. 2013; Heriansah et al. 2022; Kong et al. 2023; Liu et al. 2014; Naskar et al. 2023; Shi et al. 2013; Zamora et al. 2018). Furthermore, information regarding the effectiveness of different IMTA organism combinations, particularly the integration of sea cucumbers, bivalves, and seaweed, in improving water quality stability, enhancing fish biological performance, and generating additional economic value under minimal water management conditions is still limited. Yet

such approaches hold considerable potential for developing nursery systems that are both biologically efficient and economically viable through the reutilization of aquaculture waste (Arduini et al. 2026; Estévez Hernández et al. 2026; Lasco et al. 2026; Wang et al. 2026; Zamora et al. 2018).

Based on these research gaps, this study aims to evaluate the performance of hybrid grouper nursery culture under an Integrated Multi-Trophic Aquaculture (IMTA) system within a circular bioeconomy framework. Specifically, the study evaluates the biological performance of hybrid grouper juveniles, analyzes the effects of IMTA systems on water quality dynamics and nutrient cycling, assesses the circular utilization of aquaculture waste through extractive organisms, and examines the economic performance of IMTA-based nursery systems compared with conventional monoculture practices. The experimental design consists of a monoculture grouper treatment as a control and three IMTA combinations involving sand sea cucumber (*Holothuria* sp.), mussel, and the seaweed *Eucheuma cottonii* as extractive species.

The novelty of this study lies in the integrated evaluation of biological performance, water quality dynamics, economic performance, and circularity indicators within a hybrid grouper nursery system operated in low-cost tarpaulin tanks. While most previous IMTA studies have focused on grow-out stages in offshore cages or technologically intensive aquaculture systems, this study investigates the implementation of IMTA in small-scale nursery systems that more accurately represent the operational conditions of tropical aquaculture producers. Furthermore, this study demonstrates that trophic configurations combining deposit feeders and filter feeders provide faster improvements in ecological stability and economic performance compared with configurations emphasizing primary producers during short nursery culture periods.

2. Materials and Methods

2.1 Study site and experimental period

The experiment was conducted at a small-scale aquaculture facility in Kampung Madong, Tanjungpinang City, Riau Islands Province, Indonesia. This facility represents a typical coastal nursery system for hybrid grouper culture using tarpaulin tanks. The study was conducted from June to September 2025, covering preparation, a 28-day nursery culture experiment, and data analysis.

2.2 Ethical approval

This study received ethical approval under the research project entitled “Evaluation of Optimization and Circular Models in Hybrid Grouper (*Epinephelus* sp.) Nursery Culture Using an Integrated Multi-Trophic Aquaculture (IMTA) System” Ethical clearance was granted by the Animal Research Ethics Committee of Bogor Agricultural University (IPB University) under approval number 348-2025 IPB, issued on 2 December 2025.

2.3 Experiment design

The experiment was conducted for 28 days using a completely randomized design consisting of four treatments with three replicates each. The treatments represented different aquaculture production systems:

Treatment K: Hybrid grouper monoculture (control)

Treatment A: Hybrid grouper + sand sea cucumber (*Holothuria scabra*) + mussel (*Glaucunome virens*)

Treatment B: Hybrid grouper + sand sea cucumber (*Holothuria scabra*) + seaweed (*Eucheuma cottonii*)

Treatment C: Hybrid grouper + sand sea cucumber (*Holothuria scabra*) + mussel (*Glaucunome virens*) + seaweed (*Eucheuma cottonii*)

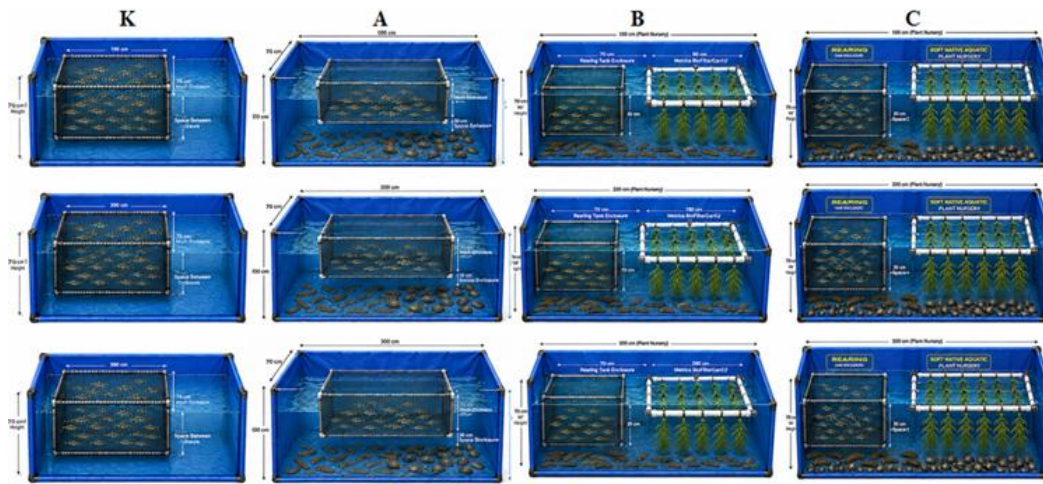


Fig. 1 Experimental layout of hybrid grouper nursery culture under monoculture and integrated multi-trophic aquaculture (IMTA) systems in tarpaulin tanks. Treatment K represents hybrid grouper monoculture as the control; treatment A represents hybrid grouper integrated with sand sea cucumber and mussel (*Glaucanome virens*); treatment B represents hybrid grouper integrated with sand sea cucumber and seaweed; and treatment C represents hybrid grouper integrated with sand sea cucumber, mussel (*Glaucanome virens*), and seaweed. Hybrid grouper juveniles were reared in net cages, while sand sea cucumber and mussel (*G. virens*) were placed at the tank bottom, and seaweed was cultivated using a floating raft system. Each treatment was arranged in three replicates.

Each treatment was designed to evaluate the performance of integrated multi-trophic aquaculture (IMTA) in improving nutrient recycling and system efficiency. The experimental treatments were arranged using a multi-species integration approach by selecting organisms representing three main functional roles in IMTA systems: deposit feeders, filter feeders, and primary producers. Sand sea cucumber (*Holothuria scabra*) was used as a deposit feeder, mussel (*Glaucanome virens*) as a filter feeder, and seaweed (*Eucheuma cottonii*) as a primary producer.

Hybrid grouper juveniles were stocked at 30 fish net cage⁻¹. The extractive species were stocked based on area-based densities according to the treatment combinations. Sand sea cucumber was stocked at 20 individuals m⁻², *G. virens* at 30 individuals m⁻², and seaweed at 500 g m⁻². These densities were applied consistently across treatments in which the respective extractive species were included. The integration of these trophic groups was expected to enhance organic waste utilization, improve environmental regulation, and support hybrid grouper nursery performance during the culture period.

Fish stocking density was based on the best treatment obtained from the first-stage experiment, namely treatment B, with a density of 30 fish net cage⁻¹. The stocking density of sand sea cucumber was set at 20 individuals m⁻² and used as a moderate experimental density in the IMTA system. This density remains within the range previously tested for sand sea cucumber weighing 30–50 g by Serang et al. (2016), although a density of 15 individuals m⁻² was reported to produce the best growth and survival performance.

Because culture-based stocking density standards for *G. virens* are still limited, the density used in this study was determined based on available ecological density data, preliminary acclimatization results, and the functional requirement of this species as a filter-feeding extractive organism in the IMTA system. The stocking density of *G. virens* was set at 30 individuals m⁻². This density was selected as an experimental density slightly higher than the reported natural density of *G. virens* in muddy coastal habitats, which ranges from 20.67 to 24.11 individuals m⁻². The use of 30 individuals m⁻² was intended to enhance the functional role of *G. virens* in removing suspended organic particles during the short nursery period, while remaining within an ecologically realistic range for controlled tank-based culture.

The seaweed stocking density was set at 500 g m⁻². Previous studies have used seaweed stocking densities of 500 g m⁻² or 0.5 kg m⁻², including Henry-Silva et al. (2023), Carton-Kawagoshi et al. (2014), de Paula Silva et al. (2012), Meichssner et al. (2021), Wang et al. (2015), and Arriesgado et al. (2024). For *cottonii/Kappaphycus*, Kunzmann et al. (2018) is particularly relevant because it used *Kappaphycus alvarezii* at 500 g m⁻² in the context of seaweed–sea cucumber integration. In addition, Hurtado et al. (2008) supports the use of 500 g based on rope-length stocking density, namely 500 g m⁻¹ line⁻¹.

Previous IMTA studies have generally incorporated only one or two extractive species, which may limit the functional capacity of the system to stabilize the culture environment and recycle nutrients. In contrast, the simultaneous integration of sand sea cucumber, *G. virens*, and seaweed remains rarely studied, particularly in high-value marine fish nursery systems in tropical regions using low-cost tarpaulin tanks.

2.5 Research parameters

The research parameters included biological performance, economic performance, water quality, and circularity performance. Biological performance was evaluated based on absolute body weight gain, absolute body length gain, specific growth rate, survival rate, feed conversion ratio, feed efficiency, and coefficient of variation in body length and body weight. Absolute body weight gain (ABWG, g) was calculated as $ABWG = W_t - W_0$, where W_t is the final mean body weight (g) and W_0 is the initial mean body weight (g). Absolute body length gain (ABLG, cm) was calculated as $ABLG = L_t - L_0$, where L_t is the final mean body length (cm) and L_0 is the initial mean body length (cm) (Nurfadillah et al. 2021; Zonneveld 2015). Specific growth rate of body weight (SGRW, % day⁻¹) was calculated as $SGRW = [(ln W_t - ln W_0) / t] \times 100$, where t is the duration of the rearing period in days. Specific growth rate of body length (SGRL, % day⁻¹) was calculated as $SGRL = [(ln L_t - ln L_0) / t] \times 100$ (Astari et al. 2023; Kurnianto et al. 2020; Puspaningsih et al. 2019). Survival rate (SR, %) was calculated as $SR = (N_t / N_0) \times 100$, where N_t is the number of fish at the end of the experiment and N_0 is the number of fish at the beginning of the experiment (Chen et al. 2025; Effendi et al. 2008). Feed conversion ratio (FCR) was calculated as $FCR = F / [(B_t + B_d) - B_0]$, where F is the total feed consumed (g), B_t is the final fish biomass (g), B_0 is the initial fish biomass (g), and B_d is the biomass of dead fish (g). Feed efficiency (FE, %) was calculated as $FE = \{[(B_t + B_d) - B_0] / F\} \times 100$ (Zonneveld 2015). The coefficient of variation (CV, %) in body length and body weight was calculated as $CV = (SD / Y) \times 100$, where SD is the standard deviation and Y is the mean value (Astari et al. 2023; Diatin et al. 2021; Samocha et al. 2015).

Economic performance was evaluated using production value, economic losses, and additional revenue generated from extractive species in the IMTA system. All economic calculations were expressed in United States dollars (USD). Total revenue from cultured biota (TRB) was calculated as the sum of the economic value generated by all harvested organisms using the formula $TRB = (N_f \times P_f) + (W_{sc} \times P_{sc}) + (W_m \times P_m) + (W_{sw} \times P_{sw})$, where N_f is the number of harvested fish, P_f is the market price per fish (USD individual⁻¹), W_{sc} is the harvested biomass of sea cucumber (kg), P_{sc} is the market price of sea cucumber (USD kg⁻¹), W_m is the harvested biomass of mussel (kg), P_m is the market price of mussel (USD kg⁻¹), W_{sw} is the harvested biomass of seaweed (kg), and P_{sw} is the market price of seaweed (USD kg⁻¹). Economic loss from mortality (ELM) was calculated as $ELM = N_d \times P_f$, where N_d is the number of dead fish during the culture period and P_f is the market price per fish (USD individual⁻¹). Economic loss from uneaten feed (ELUF) was calculated as $ELUF = W_{uf} \times P_{feed}$, where W_{uf} is the weight of uneaten feed (kg) and P_{feed} is the price of feed (USD kg⁻¹). Economic loss from solid waste (ELSW) was calculated as $ELSW = W_{swaste} \times P_{feed}$, where W_{swaste} is the weight of solid waste produced (kg) and P_{feed} is the equivalent feed value (USD kg⁻¹).

Revenue from sea cucumber production (RSC), mussel production (RM), and seaweed production (RSW) was calculated as $RSC = W_{sc} \times P_{sc}$, $RM = W_m \times P_m$, and $RSW = W_{sw} \times P_{sw}$, respectively. The total economic value of co-products (TEVCP) was calculated as $TEVCP = RSC + RM + RSW$. Waste-derived economic value (WDEV) represents the economic benefit generated through nutrient recycling by extractive species and was calculated as $WDEV = TEVCP - EL_{extractive}$, where $EL_{extractive}$ is the economic loss caused by mortality of extractive species. The increase in total income (ITI) was calculated as $ITI = TR_{IMTA} - TR_{mono}$, where TR_{IMTA} is the total revenue from the IMTA system and TR_{mono} is the total revenue from the monoculture system.

The water quality parameters observed during the experimental period included dissolved oxygen (DO), total ammonia nitrogen (TAN), ammonia (NH₃), nitrite (NO₂⁻), nitrate (NO₃⁻), phosphate (PO₄³⁻), total organic matter (TOM), total suspended solids (TSS), total dissolved solids (TDS), total solid waste, total bacterial abundance, total *Vibrio* count, and plankton density. The methods, instruments, and units used for water quality measurement included dissolved oxygen (in situ, DO meter, mg L⁻¹), salinity (in situ, refractometer, ppt), light intensity (in situ, lux meter, lx), pH (IKM/7.2.8/BPBL-B, electrometric method, scale 1–14), temperature (in situ, thermometer, °C), total nitrogen (spectrophotometric method, spectrophotometer, mg L⁻¹), ammonia (SNI 19-6964.3-2003, spectrophotometric method, spectrophotometer at 630 nm, mg L⁻¹), nitrite (SNI 19-6964.1-2003, spectrophotometric method, spectrophotometer at 543 nm, mg L⁻¹), nitrate (IKM/7.2.17/BPBL-B, colorimetric method, mg L⁻¹),

hydrogen sulfide (H₂S) gas (IKM/7.2.17/BPBL-B, colorimetric method), total organic matter (titrimetric method, Erlenmeyer flask, g kg⁻¹), solid waste weight (in situ, analytical balance with 0.01 g precision, g), total phosphorus (SNI 8567:2018, mg L⁻¹), total dissolved solids (IKM/7.2.29/BPBL-B, electrometric method, ppm), total suspended solids (IKM/7.2.10/BPBL-B, colorimetric method, mg L⁻¹), total bacteria (IKM/7.2.3/BPBL-B, pour plate agar method, CFU mL⁻¹), total *Vibrio* count (IKM/7.2.2/BPBL-B, pour plate agar method, CFU mL⁻¹), and plankton abundance (sedimentation method, Sedgwick–Rafter Counting Cell).

Circularity performance was evaluated using indicators that reflect nutrient recycling and waste valorization within the IMTA system. These indicators included solid waste reduction, improvement in water quality parameters, additional biomass production from extractive species, waste-derived economic value, nutrient recovery efficiency, waste-to-value conversion, and circularity ratio. Nutrient recovery efficiency (NRE, %) represents the capacity of the IMTA system to convert residual nutrients derived from feed inputs into secondary biomass production and was calculated as $NRE = (\text{nutrient recovered in extractive biomass} / \text{total nutrient input from feed}) \times 100$. Waste-to-value conversion (WVC, USD g⁻¹ waste) reflects the economic valorization of aquaculture waste through the production of extractive organisms and was calculated as $WVC = \text{economic value of extractive species} / \text{total waste generated}$. Circularity ratio (CR, %) represents the proportion of production output derived from recycled biomass and was calculated as $CR = (\text{recycled biomass output} / \text{total production output}) \times 100$. These indicators collectively represent the efficiency of nutrient reutilization and waste valorization within the circular bioeconomic aquaculture system.

2.6 Data Analysis

Production performance, water quality, and economic value data were statistically analyzed using ANOVA with Tukey post hoc test in JAMOV. and the results are presented as graphs or tables. Normality and homogeneity assumptions were assessed using Shapiro–Wilk and Levene tests, respectively, and most variables satisfied the assumptions required for ANOVA.

3. Results

3.1. Biological Performance of Hybrid Grouper

The biological performance of hybrid grouper juveniles under different culture treatments is presented in Figs. 2–10. Most growth, survival, and feed utilization parameters did not differ significantly among treatments ($p > 0.05$). However, the coefficient of variation in body length differed significantly among treatments ($F = 5.722$; $p = 0.022$), indicating that size uniformity varied among culture systems.

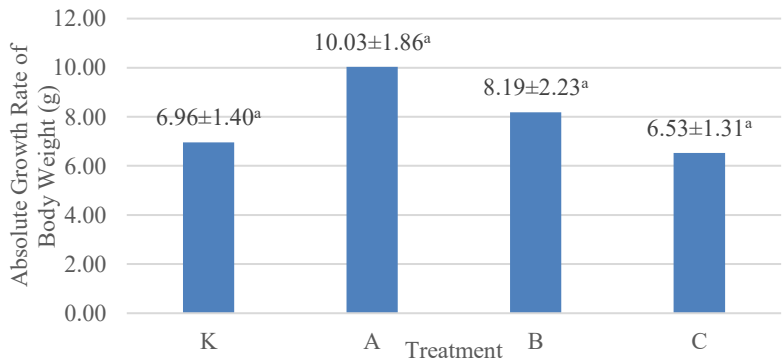


Fig. 2 Absolute growth rate of body weight in hybrid grouper juveniles reared under monoculture and IMTA systems. Values are presented as mean ± standard deviation.

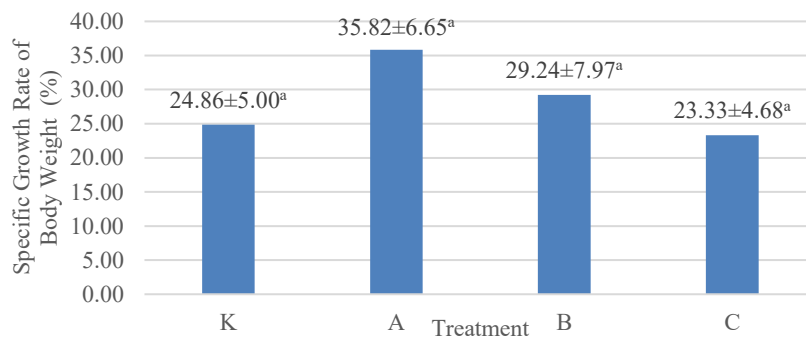


Fig. 3 Specific growth rate of body weight of hybrid grouper juveniles reared under monoculture and IMTA systems Values are presented as mean ± standard deviation.

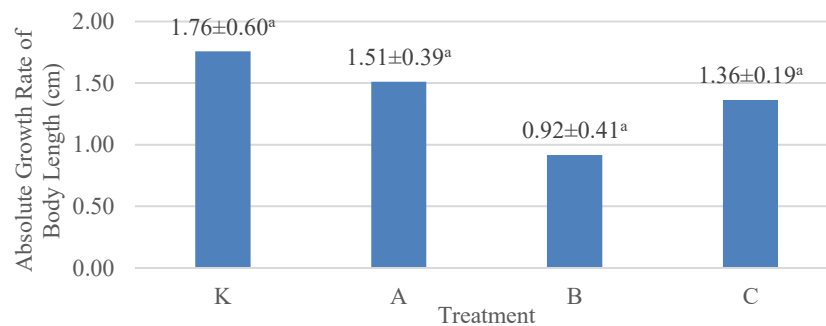


Fig. 4 Absolute growth rate of body length of hybrid grouper juveniles reared under monoculture and IMTA systems Values are presented as mean ± standard deviation.

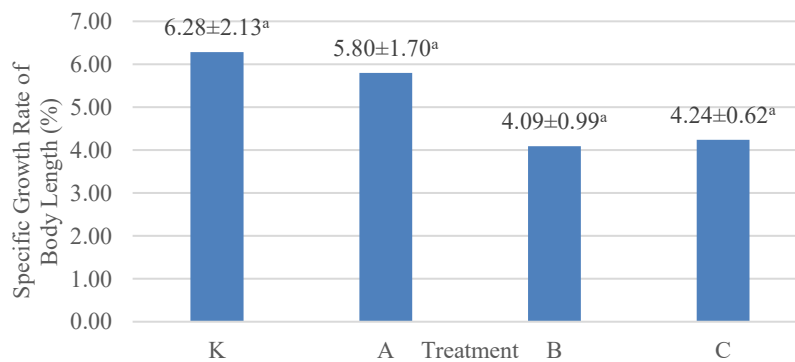


Fig. 5 Specific growth rate of body length of hybrid grouper juveniles reared under monoculture and IMTA systems Values are presented as mean ± standard deviation.

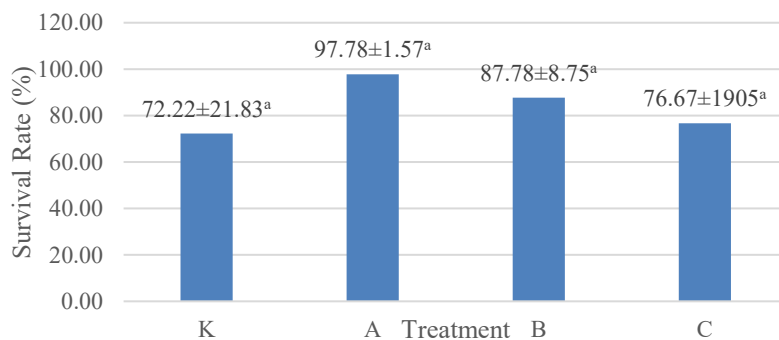


Fig. 6 Survival rate of hybrid grouper juveniles reared under monoculture and IMTA systems Values are presented as mean ± standard deviation.

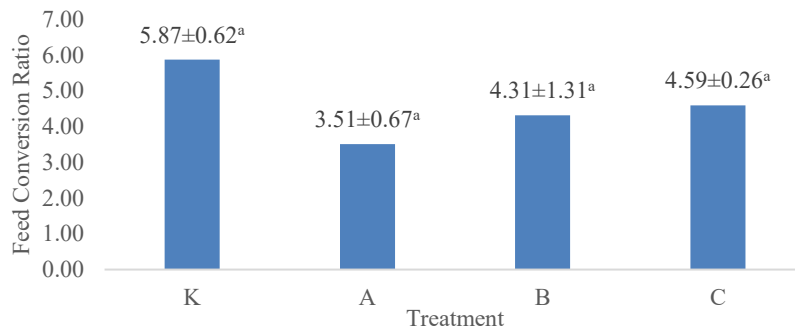


Fig. 7 Feed conversion ratio of hybrid grouper juveniles reared under monoculture and IMTA systems Values are presented as mean ± standard deviation.

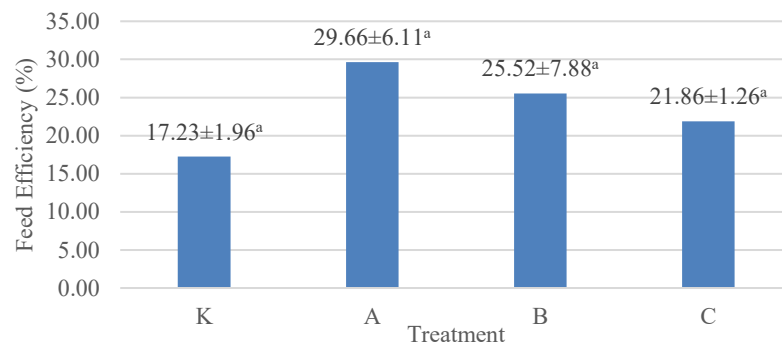


Fig. 8 Feed efficiency of hybrid grouper juveniles reared under monoculture and IMTA systems Values are presented as mean ± standard deviation.

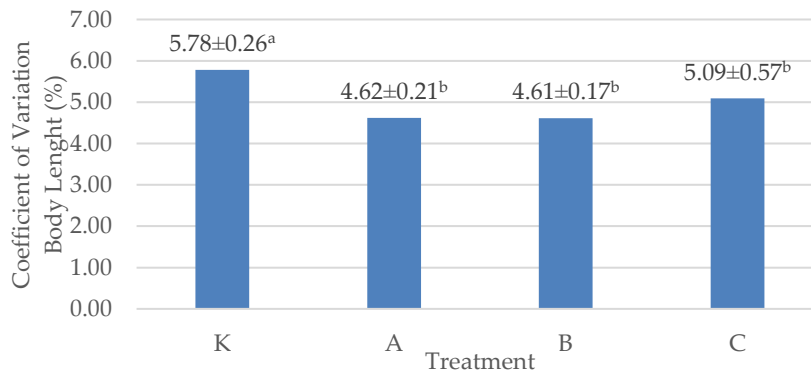


Fig. 9 Coefficient of variation body length of hybrid grouper juveniles reared under monoculture and IMTA systems Values are presented as mean ± standard deviation.

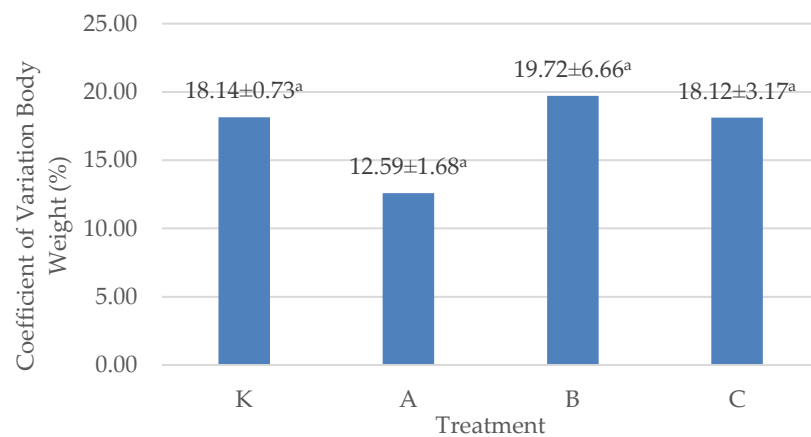


Fig. 10 Coefficient of variation of body weight of hybrid grouper juveniles reared under monoculture and IMTA systems Values are presented as mean ± standard deviation.

Absolute growth rate of body weight was numerically highest in treatment A (10.03 ± 1.86 g), followed by treatment B (8.19 ± 2.23 g), treatment K (6.96 ± 1.40 g), and treatment C (6.53 ± 1.31 g). A similar pattern was observed for the specific growth rate of body weight, with the highest value recorded in treatment A ($35.82 \pm 6.65\%$) and the lowest in treatment C ($23.33 \pm 4.68\%$). In contrast, absolute and specific growth rates of body length were numerically highest in the monoculture treatment K, reaching 1.76 ± 0.60 cm and $6.28 \pm 2.13\%$, respectively.

Feed utilization tended to improve under IMTA conditions. The lowest feed conversion ratio was recorded in treatment A (3.51 ± 0.67), followed by treatment B (4.31 ± 1.31), treatment C (4.59 ± 0.26), and treatment K (5.87 ± 0.62). Consistently, feed efficiency was highest in treatment A ($29.66 \pm 6.11\%$) and lowest in treatment K ($17.23 \pm 1.96\%$). Survival rate was also numerically highest in treatment A ($97.78 \pm 1.57\%$), followed by treatment B ($87.78 \pm 8.75\%$), treatment C ($76.67 \pm 19.05\%$), and treatment K ($72.22 \pm 21.83\%$).

The coefficient of variation in body length was significantly higher in the monoculture treatment than in the IMTA treatments, suggesting that trophic integration contributed to improved size uniformity among hybrid grouper juveniles. The coefficient of variation in body weight ranged from $12.59 \pm 1.68\%$ in treatment A to $19.72 \pm 6.66\%$ in treatment B. Overall, treatment A showed the most favorable nursery performance, particularly in terms of survival, feed conversion ratio, and feed efficiency, although most biological parameters did not differ significantly among treatments.

3.2 Economic performance

Economic performance indicators under different culture treatments are summarized in Table 1. One-way ANOVA indicated that total revenue from cultured biota (TRB), economic loss from mortality (ELM), and economic loss from solid waste (ELSW) did not differ significantly among treatments ($p > 0.05$). However, economic loss from uneaten feed (ELUF) differed significantly among treatments ($F = 6.925$; $p = 0.013$). Although total revenue did not differ significantly, the IMTA treatments showed numerically higher economic returns than the monoculture system.

Table 1. Economic performance of hybrid grouper nursery culture under IMTA and monoculture systems (USD).

Parameter	Average Economic Return (USD)			
	K	A	B	C
Total revenue from cultured biota	78.61	134.64	103.16	101.44
Economic loss from mortality (elm)	10.210	4.355	10.167	12.360
Economic loss from uneaten feed (eluf)	0.096	0.069	0.044	0.058
Economic loss from solid waste (elsw)	0.289	0.287	0.206	0.206
Revenue from sea cucumber production	0.000	22.020	18.260	20.409
Revenue from mussel production	0.000	3.437	0.000	3.276
Revenue from seaweed production	0.000	0.000	0.000	0.000
Increase in total income	0.000	49.165	26.442	20.287
Increase in production output (indv)	0.000	0.008	0.003	0.006
Increase in grouper survival rate (%)	0.000	0.002	0.001	0.000
Reduction in waste-related economic loss	0.000	-0.082	-0.156	-0.113
Total economic value of co-products	0.000	25.457	18.260	23.685
Added economic value from waste recycling into co-products	0.000	25.169	17.972	23.396
Total economic loss from fish mortality	10.210	1.185	4.170	8.071
Total economic loss from extractive species mortality	0.000	3.171	5.997	4.609

Treatment A produced the highest total revenue from cultured biota (USD 134.64), followed by treatment B (USD 103.16), treatment C (USD 101.44), and the monoculture treatment K (USD 78.61). Economic loss from mortality was lowest in treatment A (USD 4.355), whereas the highest value was recorded in treatment C (USD 12.360). Treatments K and B showed relatively similar mortality-related losses, with values of USD 10.210 and USD 10.167, respectively. Economic loss from uneaten feed ranged from USD 0.044 to USD 0.096, with the lowest value observed in treatment B and the highest value observed in the monoculture treatment. Economic loss from solid waste was slightly lower in treatments B and C (USD 0.206) than in treatment K (USD 0.289) and treatment A (USD 0.287).

Additional economic value in the IMTA systems was generated through the production of extractive species. Sea cucumber production contributed USD 22.020 in treatment A, USD 18.260 in treatment B, and USD 20.409 in treatment C. Mussel production generated additional revenue of USD 3.437 in treatment A and USD 3.276 in treatment C, whereas no measurable revenue from seaweed production was recorded during the experimental period. Consequently, the total economic value of co-products was highest in treatment A (USD 25.457), followed by treatment C (USD 23.685) and treatment B (USD 18.260).

Compared with the monoculture treatment, the IMTA treatments increased total income, with the highest increase observed in treatment A (USD 49.165), followed by treatment B (USD 26.442) and treatment C (USD 20.287). The added economic value derived from waste recycling into co-products was also highest in treatment A (USD 25.169), followed by treatment C (USD 23.396) and treatment B (USD 17.972). These results indicate that the integration of extractive species enhanced the economic performance of hybrid grouper nursery culture by generating additional co-product value and partially converting aquaculture waste into economically useful biomass.

3.3 Water Quality Parameters

Water quality parameters measured during the 28-day nursery culture period are presented in Figs. 11–18. The monitored parameters included total solid waste biomass, ammonia, nitrate, nitrite, phosphate, total organic matter (TOM), plankton abundance, and total *Vibrio* count.

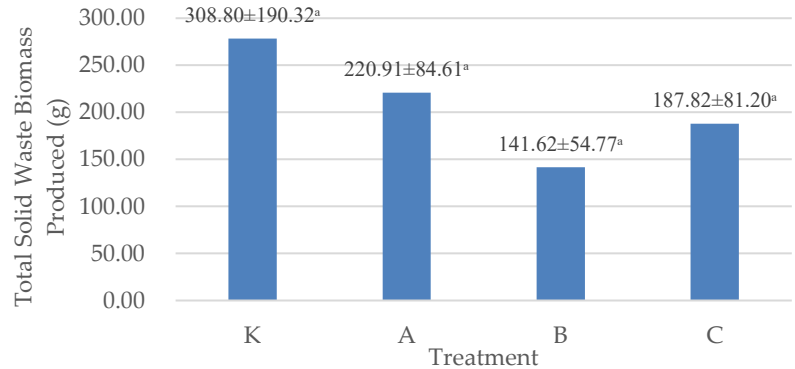


Fig. 11 Total solid waste biomass produced in hybrid grouper nursery systems under different culture treatments Values are presented as mean ± standard deviation

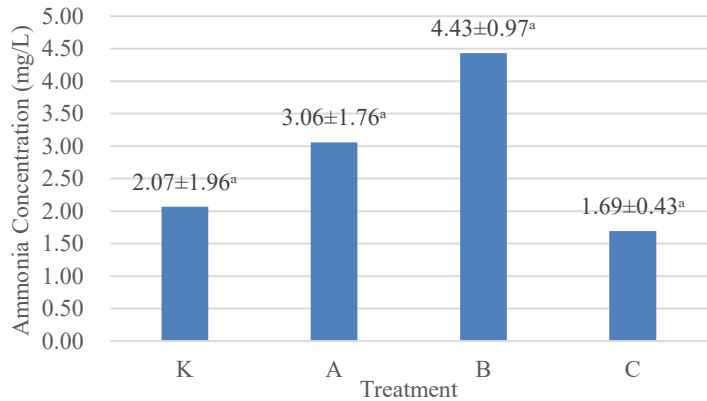


Fig. 12 Ammonia concentration in hybrid grouper nursery systems under different culture treatments Values are presented as mean ± standard deviation.

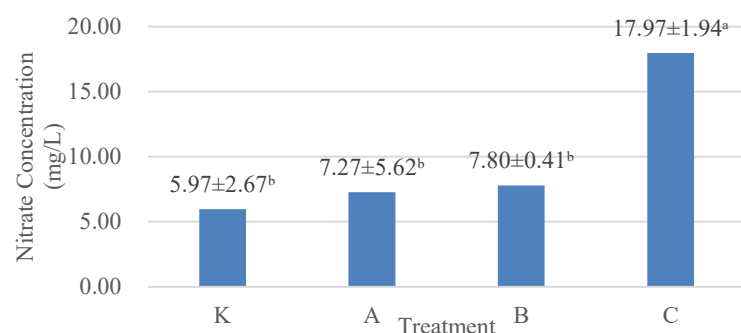


Fig. 13 Nitrate concentration in hybrid grouper nursery systems under different culture treatments Values are presented as mean ± standard deviation

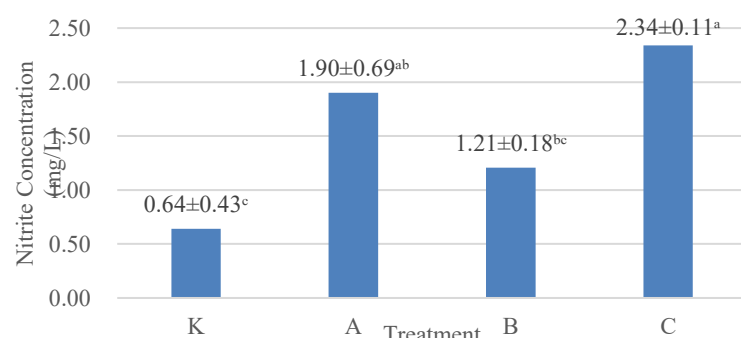


Fig. 14 Nitrite concentration in hybrid grouper nursery systems under different culture treatments Values are presented as mean ± standard deviation.

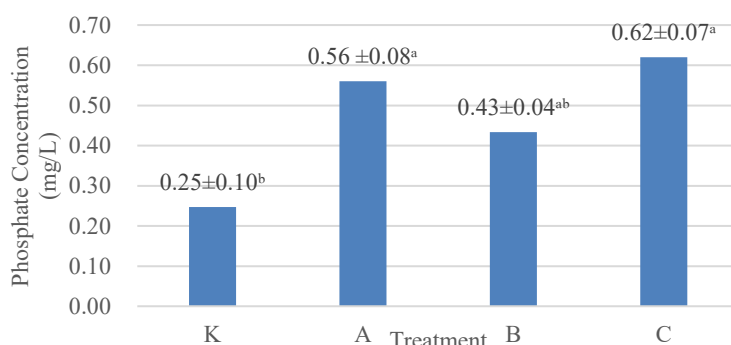


Fig. 15 Phosphate concentration in hybrid grouper nursery systems under different culture treatments Values are presented as mean ± standard deviation.

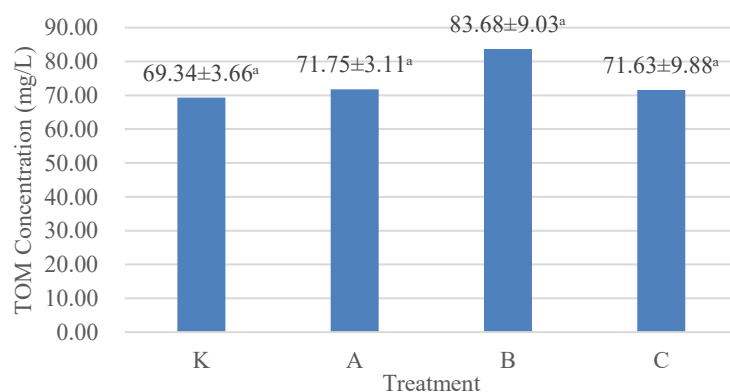


Fig. 16 TOM concentration in hybrid grouper nursery systems under different culture treatments Values are presented as mean ± standard deviation.

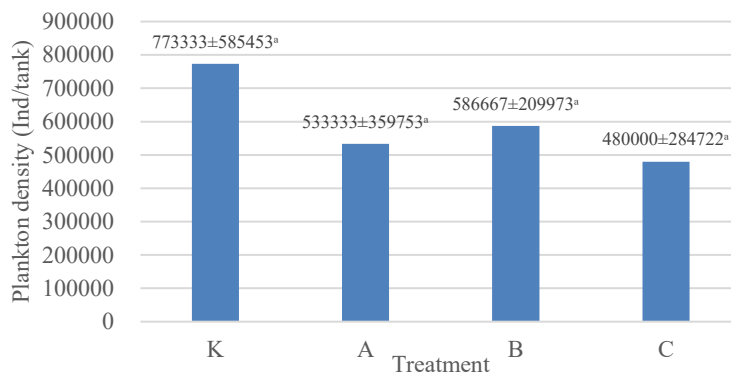


Fig. 17 Plankton density in hybrid grouper nursery systems under different culture treatments Values are presented as mean ± standard deviation

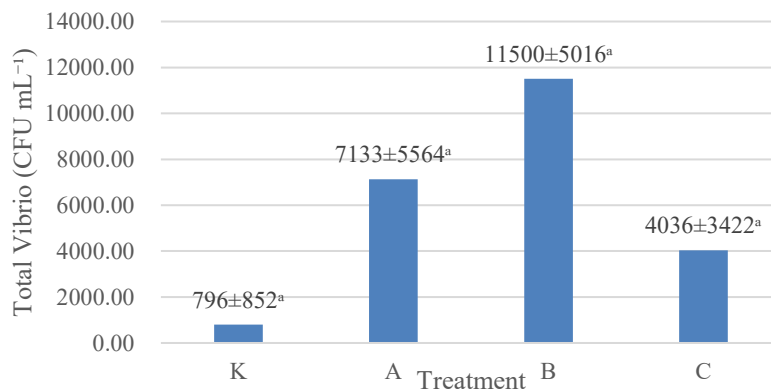


Fig. 18 Total Vibrio count in hybrid grouper nursery systems under different culture treatments Values are presented as mean ± standard deviation

Total solid waste accumulation was highest in the monoculture treatment, reaching 278.35 g. In comparison, lower values were recorded in the IMTA treatments, including 220.91 g in treatment A, 141.62 g in treatment B, and 187.82 g in treatment C. Ammonia concentrations ranged from 1.69 to 4.43 mg L⁻¹. The lowest ammonia concentration was observed in treatment C, whereas the highest value was recorded in treatment B. Nitrate concentrations ranged from 5.97 to 17.97 mg L⁻¹, with the highest value observed in treatment C, while lower values were recorded in treatments K, A, and B. Nitrite concentrations ranged from 0.64 to 2.34 mg L⁻¹, with the highest value observed in treatment C. Phosphate concentrations ranged from 0.25 to 0.62 mg L⁻¹, with the highest concentration also recorded in treatment C.

Total organic matter concentrations ranged from 69.34 to 83.68 mg L⁻¹ and showed moderate variation among treatments, with the highest value recorded in treatment B. Biological indicators also varied among treatments. The highest plankton abundance was recorded in the monoculture treatment (773,333 individuals tank⁻¹), while lower values were observed in the IMTA treatments. Total *Vibrio* count varied among treatments, with the highest value recorded in treatment B (11,500 CFU mL⁻¹), whereas lower values were observed in treatments K, A, and C. Overall, these results indicate that IMTA influenced solid waste accumulation, nutrient dynamics, plankton abundance, and microbial conditions within the hybrid grouper nursery environment.

3.4 Circular Performance

Circular system performance was evaluated based on changes in water quality parameters, waste reduction, nutrient reutilization, and circularity indicators during the 28-day culture period. The results are summarized in Table 2. Several environmental parameters decreased during the experiment, including dissolved oxygen (DO), total dissolved solids (TDS), pH, and hydrogen sulfide (H₂S).

Table 2. Environmental Regulation, Nutrient Recycling, and Circularity Performance in IMTA-Based Hybrid Grouper Nursery Systems

Parameters	Unit	Mean Change in Water Quality Parameters			
		K	A	B	C
Dissolved Oxygen	mg L ⁻¹	-0.80	-0.43	-1.53	-1.23
Total Nitrogen in Water	mg L ⁻¹	-0.68	-0.49	0.36	0.10
Total Nitrogen in Solid Waste	%	1.84	2.57	2.54	2.56
Total Ammonia Nitrogen	mg L ⁻¹	-0.10	-0.41	0.15	-0.01
Ammonia	mg L ⁻¹	0.51	3.05	4.39	1.65
Phosphate	mg L ⁻¹	0.26	0.52	0.39	0.58
Nitrite	mg L ⁻¹	0.93	1.87	1.18	2.31
Nitrate	mg L ⁻¹	4.83	4.97	5.30	15.17
Hydrogen Sulfide	mg L ⁻¹	-0.01	-0.07	0.00	-0.01
Total Phosphorus in Solid Waste	mg L ⁻¹	0.94	1.03	0.91	0.95
Total Organic Matter	mg L ⁻¹	2.19	39.02	38.94	15.39
Total Dissolved Solids	mg L ⁻¹	-300	-467	-1133	-500
Total Suspended Solids	mg L ⁻¹	-13.77	-0.67	3.17	-2.67
Total Bacterial Count	CFU mL ⁻¹	5067	-14877	393	-29963
Total Vibrio count Count	CFU mL ⁻¹	-1150	6873	11100	3317
Temperature	°C	-1.67	-2.07	-1.80	-1.70
Salinity	ppt	1.33	0.00	-0.67	0.67
pH		-0.29	-0.48	-0.45	-0.57
Carbon Dioxide	mg L ⁻¹	-0.07	0.33	0.23	0.50
Plankton Abundance	ind m ⁻³	-400000	-426667	-213333	-160000
Light Intensity	lux	-1586.0	-465.7	-266.3	148.0
Total Solid Waste Biomass	g	308.8	220.9	141.6	187.8
Total Revenue	USD	78.61	134.64	103.16	101.44
Co-product Value	USD	0	25.46	18.26	23.68
Waste-to-Value Conversion	USD/g waste	0	0.12	0.13	0.13
Circularity Ratio	(%)	0	18.91	17.7	23.35
Waste Reduction vs Monoculture	(%)	0	28.47	54.15	39.18

Among these variables, the largest reduction in TDS was observed in treatment B (−1133 mg L⁻¹), followed by treatment C (−500 mg L⁻¹) and treatment A (−467 mg L⁻¹), indicating changes in dissolved solid dynamics within the IMTA systems. Total suspended solids (TSS) also decreased in most IMTA treatments, although a slight increase was recorded in treatment B.

In contrast, several nutrient-related parameters, including ammonia, nitrite, nitrate, phosphate, and total organic matter (TOM), increased during the culture period. This increase reflects continuous nutrient loading from feeding activities, uneaten feed, fecal waste, and organic matter decomposition. Nevertheless, the IMTA systems reduced solid waste accumulation compared with the monoculture treatment. The monoculture system produced the highest total solid waste biomass (308.8 g), whereas lower values were observed in treatment A (220.9 g), treatment B (141.6 g), and treatment C (187.8 g). The highest waste reduction relative to monoculture was achieved in treatment B (54.15%), followed by treatment C (39.18%) and treatment A (28.47%).

From a circular bioeconomy perspective, the IMTA treatments demonstrated partial nutrient reutilization and waste valorization through trophic integration among cultured organisms. This was reflected by the production of additional biomass from extractive species, higher total revenue in the IMTA treatments, and the generation of co-product economic value derived from aquaculture waste streams. Waste-to-value conversion ranged from 0.12 to 0.13 USD g⁻¹ waste in the IMTA treatments, while the circularity ratio ranged from 17.70% to 23.35%, with the highest value observed in treatment C. These findings indicate that residual nutrients originating from uneaten feed and fish feces were partially redirected into productive biological pathways through the activities of deposit feeders, filter feeders, and primary producers.

Furthermore, the IMTA treatments showed numerically higher economic returns than the monoculture system. Total revenue increased from USD 78.61 in the monoculture treatment to USD

134.64, USD 103.16, and USD 101.44 in treatments A, B, and C, respectively. The integration of extractive species also generated additional economic value through secondary biomass production and contributed to the partial conversion of aquaculture waste into useful co-products. These results indicate that IMTA can function as a partially circular aquaculture strategy that supports nutrient recycling, resource valorization, and blue circular bioeconomy development in hybrid grouper nursery culture systems.

4. Discussion

The results of this study demonstrate that integrated multi-trophic aquaculture (IMTA) influenced several components of the hybrid grouper nursery system, including biological performance, environmental regulation, and economic outcomes. However, the responses were not uniform across all measured parameters. Most growth parameters did not differ significantly among treatments, indicating that the IMTA configurations did not directly accelerate hybrid grouper growth during the relatively short 28-day nursery period. Nevertheless, improvements were observed in survival rate, feed utilization, size uniformity, solid waste reduction, and additional economic value. This suggests that IMTA contributed more strongly to system stabilization and resource-use efficiency than to immediate growth enhancement. This interpretation is consistent with the general concept of IMTA, in which extractive organisms are integrated with fed aquaculture species to recover residual nutrients, reduce waste accumulation, and generate additional biomass (Cubillo et al. 2016; Zamora et al. 2016; Rusco et al. 2024).

The absence of significant differences in most growth parameters suggests that the duration of the nursery trial may have been too short for trophic integration to produce measurable differences in fish growth. In short nursery cycles, environmental improvement may first be reflected in survival, feed conversion, and size uniformity rather than in absolute biomass gain. A similar pattern has been discussed in IMTA studies showing that system-level benefits are often expressed through improved nutrient retention, reduced waste loading, and better production efficiency rather than immediate growth acceleration of the fed species (Huo et al. 2024; Rusco et al. 2024). In the present study, treatment A showed the most favorable numerical performance, particularly in survival rate, feed conversion ratio, and feed efficiency. This indicates that the combination of hybrid grouper, sand sea cucumber, and mussel provided a more favorable nursery environment than monoculture.

A particularly important biological response was the significant difference in the coefficient of variation in body length among treatments. The lower variation in body length observed in the IMTA treatments indicates that trophic integration may improve size uniformity among hybrid grouper juveniles. Size uniformity is an important production attribute in nursery systems because heterogeneous fish size can increase competition, social dominance, and cannibalism risk. Therefore, although growth improvement was not statistically significant, the reduction in length variation suggests that IMTA may support more stable and uniform juvenile production. This finding is important because nursery success is not determined only by growth rate, but also by survival, uniformity, feed efficiency, and the production of healthy juveniles for the grow-out phase.

From an ecological perspective, the IMTA treatments showed stronger effects on particulate waste regulation than on dissolved nutrient control. In monoculture systems, uneaten feed and fish feces tend to accumulate as particulate organic matter, contributing to sludge formation, oxygen demand, and nutrient loading. In contrast, the inclusion of extractive organisms provided additional biological pathways for waste utilization. Sea cucumbers function as deposit feeders by consuming organic matter deposited at the tank bottom, while mussels function as filter feeders by capturing suspended organic particles from the water column. Seaweed functions as a primary producer that assimilates dissolved nutrients such as nitrogen and phosphorus. These complementary trophic roles are consistent with the IMTA principle that organic and inorganic waste streams from fed species can be redirected into extractive biomass (Cubillo et al. 2016; Zamora et al. 2016; Checa et al. 2024).

The role of sand sea cucumber in this study is particularly relevant to particulate organic waste management. Deposit-feeding sea cucumbers have been widely discussed as effective nutrient recyclers and processors of particulate waste in IMTA systems because they ingest organic-rich sediments, uneaten feed residues, and fecal particles, thereby contributing to sediment remediation and organic matter processing (Zamora et al. 2016). Model-based IMTA studies also indicate that deposit feeders placed below fed aquaculture units can remove substantial particulate organic loading and convert part of this waste into harvestable biomass (Cubillo et al. 2016). This mechanism helps explain why treatments involving sand sea cucumber showed lower solid waste accumulation than monoculture.

The mussel component also contributed to the ecological function of the IMTA system. Filter-feeding bivalves can capture suspended organic particles, phytoplankton, bacteria, and fine particulate

matter in the water column, thereby reducing suspended solids and improving particle transfer within the culture system. Recent studies on land-based IMTA systems involving fish, mussels, and macroalgae have shown that mussels and macroalgae can improve water quality and contribute to nutrient and particle removal (Batir et al. 2024; Huo et al. 2024). In the present study, treatment A, which combined deposit-feeding sea cucumber and filter-feeding mussel, produced the best overall bioeconomic response. This suggests that in short-term nursery systems with high feeding intensity, the combined regulation of bottom-deposited waste and suspended organic particles may be more immediately beneficial than relying primarily on dissolved nutrient uptake.

However, the present study also shows that IMTA did not fully control dissolved inorganic nutrients during the 28-day culture period. Concentrations of ammonia, nitrite, nitrate, phosphate, and total organic matter remained relatively high in some IMTA treatments. This indicates that the nutrient assimilation capacity of the system, particularly by seaweed, was not sufficient to fully balance nutrient inputs from intensive feeding. Several factors may explain this condition, including short culture duration, trophic biomass ratio, nutrient retention time, water exchange, and environmental conditions affecting seaweed photosynthesis. Batir et al. (2024) reported substantial reductions in ammonia, nitrate, and nitrite in a 90-day land-based IMTA system involving fish, mussels, and sea lettuce, suggesting that longer retention time and optimized macroalgal biomass may be required to achieve stronger dissolved nutrient removal. Therefore, the present IMTA system should be interpreted as a partial circular system that was more effective in regulating particulate organic waste than in completely removing dissolved nutrients.

The microbial response also requires careful interpretation. Although reduced organic waste may theoretically reduce environmental stress, the present results did not show a consistent reduction in *Vibrio* abundance across all IMTA treatments. The highest *Vibrio* abundance was observed in the treatment involving sand sea cucumber and seaweed. This indicates that microbial dynamics in IMTA systems are complex and may be influenced not only by organic waste availability, but also by nutrient concentration, organic substrates, species interactions, and water exchange conditions. Therefore, the role of IMTA in controlling *Vibrio* should not be overgeneralized based on the present short-term nursery trial. Instead, microbial dynamics should be considered an important area for further study in tarpaulin-tank IMTA systems.

The economic results support the potential of IMTA as a bioeconomic strategy for hybrid grouper nursery culture. Although total revenue from cultured biota did not differ significantly among treatments, IMTA treatments showed numerically higher total revenue than monoculture. Treatment A produced the highest total revenue from cultured biota, followed by treatments B and C, while the monoculture treatment produced the lowest revenue. The improvement in treatment A was mainly associated with higher fish survival, better feed utilization, and additional revenue from extractive species. Sea cucumber and mussel production contributed directly to co-product value, demonstrating that residual nutrients and organic waste can be partially converted into economically useful biomass. This is consistent with the circular bioeconomy concept in aquaculture, which emphasizes nutrient recovery, resource-use efficiency, waste valorization, and production diversification (Verreth et al. 2023; Checa et al. 2024).

An important finding of this study is that different IMTA configurations produced different functional advantages. Treatment A, which combined hybrid grouper with sand sea cucumber and mussel, provided the most favorable bioeconomic performance, particularly in survival, feed conversion ratio, feed efficiency, total revenue, and co-product value. In contrast, treatment B, which included seaweed, achieved the highest solid waste reduction but did not generate the highest economic return. This indicates that short-term IMTA performance in nursery systems involves a trade-off between ecological regulation and economic output. The seaweed-based treatment contributed strongly to waste reduction and nutrient regulation, but no measurable seaweed revenue was recorded during the experimental period. Thus, in short nursery cycles, seaweed may function more as an ecological component than as an immediate economic product. Its economic contribution may become more evident in longer culture periods or with improved seaweed biomass management.

Another important finding is that the most complex IMTA configuration was not necessarily the most effective. Treatment C included sand sea cucumber, mussel, and seaweed, but it did not produce the best biological or economic performance. This suggests that adding more trophic components does not automatically improve nursery performance. In small tarpaulin tanks, excessive trophic complexity may increase biological interactions, competition for space, organic loading, or management difficulty. Therefore, IMTA design should not only focus on the number of species integrated, but also on the functional balance among fed species, deposit feeders, filter feeders, and primary producers. Recent circularity assessments of IMTA systems also emphasize that nutrient management and resource-use

efficiency are central indicators of IMTA performance, meaning that species combinations must be evaluated based on functional efficiency rather than complexity alone (Checa et al. 2024).

The circularity indicators observed in this study show that IMTA partially transformed a linear nutrient pathway into a more circular production model. In conventional monoculture systems, residual nutrients from uneaten feed and feces tend to accumulate as waste. In the IMTA systems, part of these residual nutrients was redirected into secondary biomass through the activities of extractive organisms. This process generated waste-derived economic value and improved the circularity ratio of the production system. However, because dissolved nutrient accumulation was still observed, the system should be considered partially circular rather than fully closed-loop. This interpretation is consistent with recent circular bioeconomy frameworks in aquaculture, which state that circularity should be assessed through measurable improvements in nutrient recovery, resource efficiency, waste reduction, and co-product generation rather than by assuming that all integrated systems are fully circular (Verreth et al. 2023; Checa et al. 2024).

Overall, the findings indicate that IMTA can improve the sustainability of hybrid grouper nursery culture by enhancing survival, improving feed utilization, reducing solid waste, and generating additional co-product value. The most effective short-term configuration was the integration of hybrid grouper with sand sea cucumber and mussel, suggesting that deposit feeder–filter feeder integration provides rapid ecological and economic benefits in intensive nursery systems. Seaweed integration contributed more clearly to solid waste reduction and nutrient regulation, but its economic value was not realized within the 28-day nursery period. Future studies should optimize trophic biomass ratios, extend culture duration, improve seaweed management, and evaluate microbial dynamics more comprehensively to strengthen the circular bioeconomic performance of IMTA-based nursery systems.

The novelty of this study lies in the integrated evaluation of biological performance, environmental dynamics, economic performance, and circularity indicators within a hybrid grouper nursery system operated in low-cost tarpaulin tanks. While most previous IMTA studies have focused on grow-out systems, offshore cages, or technologically intensive aquaculture facilities, this study provides empirical evidence from a small-scale nursery system that more closely represents tropical aquaculture practices. These findings provide practical insights for designing IMTA configurations that are not only environmentally functional but also economically relevant for high-value marine fish nursery production.

5. Conclusions

The results of this study demonstrate that integrated multi-trophic aquaculture (IMTA) enhanced several aspects of ecological regulation, nutrient reutilization, and bioeconomic performance in hybrid grouper nursery culture. Compared with monoculture, IMTA reduced solid waste accumulation, improved feed utilization, increased survival rate, and generated additional economic value through extractive species production.

Among the evaluated treatments, the hybrid grouper–sand sea cucumber–mussel combination provided the most favorable bioeconomic performance, particularly in survival rate, feed conversion ratio, feed efficiency, total revenue, and co-product value. In contrast, the hybrid grouper–sand sea cucumber–seaweed treatment achieved the highest solid waste reduction, indicating that different IMTA configurations provide different functional advantages. The observed waste-to-value conversion and circularity ratio show that part of the residual nutrients and organic waste was converted into economically valuable secondary biomass through trophic nutrient recycling.

Overall, these findings indicate that IMTA can function as a partially circular aquaculture strategy that supports nutrient recycling, resource valorization, and blue circular bioeconomy development in intensive marine fish nursery systems. Further optimization of trophic biomass ratios, seaweed biomass, and culture duration is required to improve dissolved nutrient assimilation and strengthen system circularity.

CRediT authorship contribution statement

Wiwin Kusuma Atmaja Putra: conceptualization, Investigation, data collection, writing original draft; Irzal Effendi: supervision, methodology validation, writing, review and editing; Iis Diatin: supervision, methodology, writing, review and editing; Tatag Budiardi: supervision, project administration, writing, review, and editing dan Luky Andrianto: supervision, validation, writing, review and editing.

Declaration of Competing Interest

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Data availability

Data will be made available on request.

Conflicts of Interest: The author state that they have no competing interests regarding the preparation of this research manuscript.

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Highlights

IMTA increased hybrid grouper survival up to 97.78%.
Solid waste biomass was reduced by up to 54.15% under IMTA.
Waste-to-value conversion reached 0.13 USD g⁻¹ waste.
Deposit feeder–filter feeder integration improved bioeconomic performance.
IMTA supported nutrient recycling in a circular aquaculture framework.

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